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CONTROL AND MAINTENANCE PROCESSES IN WORKING MEMORY: NEUROPSYCHOLOGICAL INVESTIGATIONS

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DECLARATION

I, Raffaella Moro, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

This work is lovingly dedicated to my dad, Paolo, with thanks for who he is and who he has allowed me to become. It is also warmly dedicated to my mum, Maria, who is part of me, still.

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I am also grateful to all the patients and healthy participants who took part in this study, for their time and valuable efforts.

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ABSTRACT

The aim of this thesis was to investigate working memory by investigating performance on an updating task devised to pose variable demands on maintenance and control processes. The task required participants to recall information that was "relevant" according to a given criterion, at the same time inhibiting information that was not relevant to that criterion. Performance on this task was investigated in healthy participants, in order to understand the impact of different loads on maintenance and inhibition processes, and of different stimuli on recall performance and on error production. The predictions tested were that recall performance on the updating task would be affected by both load on maintenance and load on control processes and that the production of errors due to the recall of "to-be-inhibited" information would only be affected by load on control processes. The hypothesis that the central executive component of working memory would be differentially affected by normal aging, dementia of the Alzheimer's type and brain damage affecting the prefrontal lobes was also explored by investigating performance on the updating task in groups with these characteristics. The predictions were that in normal ageing maintenance would be reduced but control processes would be spared, in senile dementia both processes would be impaired and in presence of prefrontal damage only control processes would be affected. Moreover, since the multi-component model of working memory was originally conceived as the basis for complex cognitive abilities such as mental arithmetic, this was also investigated in groups of participants reported in the literature as having problems in these functions as well as in working memory. The findings are discussed in light of the predictions.

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CHAPTER 1: INTRODUCTION

Memory is the ability to encode, store, retrieve and organise information acquired from the environment. The use of a single term could be misleading, because memory is not a unitary system, but is composed of several systems with differential storage capacity (from the limited capacity of short term memory - STM- to the almost unlimited capacity of long term memory -LTM) and length of memory trace (from few seconds to a whole life). Most cognitive processes require memory and every intelligent being has some sort of memory system that plays a critical role in its most complex cognitive functions.

The importance of memory in our lives is highlighted by the fact that memory has been a source of speculation by philosophers and scientists for centuries. A scientific approach to the study of memory began one century ago with the experiments of Hermann Ebbinghaus (1885) on the mechanisms of learning and forgetting lists of unrelated words and pseudo-words. This was the first attempt to rigidly control experimental conditions in the study of human memory, and allowed a better understanding of the capacity of the memory system. However, the experiments left unexplored the validity of these findings outside the laboratory and the applicability of the findings to issues such as rehabilitation of patients with memory difficulties. From the 1960s memory became one of the more active areas of cognitive psychology, and the focus of research in this field became more theoretical, using the analogy of the human brain as a computer which stores and processes information. The subdivision of the memory system began in this era, with emerging empirical evidence and models of sub-systems being proposed. One source of evidence came from findings suggesting immediate memory for verbal material relies on phonological coding (Baddeley, 1966a) whereas long-term memory relies on semantic coding (Baddeley, 1966c). During performance on certain memory tasks, two components came to light: the primacy and recency effects. When participants are presented with a list of words for free recall, they will preferentially recall the last few items presented (recency effect), and the first few items of the list (primacy effect). If there is a delay between the presentation of the list and recall, for example with a task of interpolate counting, the recency effect will tend to disappear but the primacy effect will remain unchanged (Glanzer & Cunitz, 1966). This has been interpreted as an indication that the last few items are held in a short-term memory store whereas the earlier items are stored in long-term memory. Additional evidence which speaks to this interpretation comes from the finding that variables that influence long-term learning (e.g. presentation rate, word frequency, distraction during learning) will influence the recall of earlier items but not of the last few items of the list (Glanzer, 1972).

Another, and maybe the most influential, source of evidence for the presence of separate memory systems, comes from neuropsychological studies. Patients suffering from an amnesic syndrome, typically associated with lesions to the temporal lobes or hippocampal areas (Tranel & Damasio, 1995) show impaired learning of new material and recollection of recent biographical events (O'Connor, Verfaellie, & Cermak, 1995), but preserved digit span and recency effects in free recall (Baddeley & Warrington, 1970). The opposite presentation was documented in a patient with damage to the perisylvian region of the left hemisphere: this patient had a digit span of two and a limited recency effect in free recall, but normal long-term learning (Shallice & Warrington, 1970).

This accumulated evidence led to the abandonment of the concept of a unitary memory system. Following this, the most influential approach was what came to be called the "modal model" of Atkinson and Shiffrin (1968) (see figure 1.1). According to this model, information from the environment enters a series of sensory registers, which pass the information to a short-term store. Information must pass through this store in order to be transferred into the long-term store. The longer information resides in the short-term store, the more likely it is to pass into the long-term store. In Atkinson and Shiffrin's model, the short-term store plays a crucial role for cognition in general.

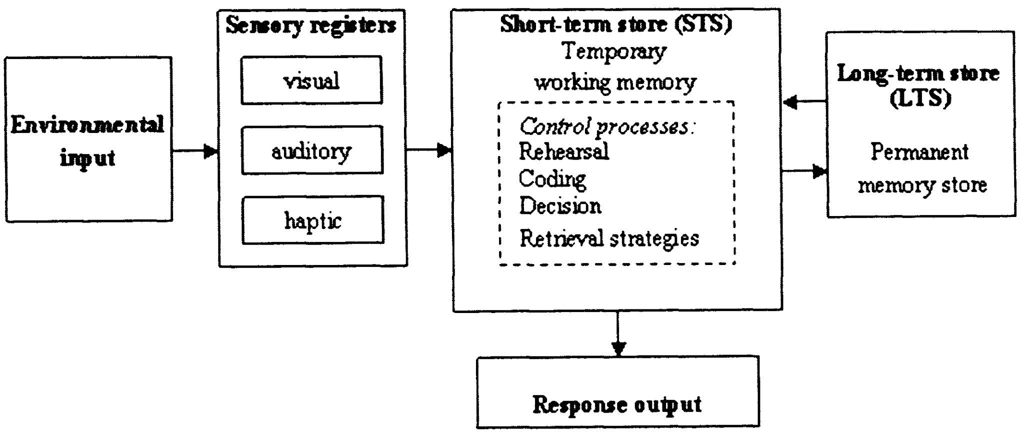

Figure 1. 1: The modal model proposed by Atkinson & Shiffrin (Atkinson & Shiffrin, 1968)

1.1. From the concept of Short Term Memory (STM) to the concept of a Working Memory (WM)

Atkinson and Shiffrin's model, however, proved to be quite problematic and was unable to explain the empirical data. Other frameworks, such as the Levels of Processing approach (Craik & Lockhart, 1972), gave a better account of learning than the simplistic idea that merely holding an item in the short-term system would be enough for learning (Craik & Watkins, 1973). Craik and Lockhart (1972) suggested, in fact, that the duration of a memory trace was a direct result of the level of encoding, with deeper encoding leading to longer lasting memory traces. Moreover, the evidence from Shallice and Warrington's (1970) patient showed that long-term learning was possible with an impairment of the short-term store and that such an impairment caused very few problems in everyday life. This seemed to argue against the central importance of the short-term store for cognition implied by the modal model. Baddeley and Hitch (1974), proposed that a solution to these problems was to abandon the assumption of an unitary short-term store, and suggested a multi-component WM system. They demonstrated this by asking participants to perform complex cognitive tasks (e.g. understanding written text or solving a mathematical problem) while retaining other information (e.g. a list of numbers) in the STM store. They found that their participants were able to perform complex cognitive tasks with an acceptable accuracy, albeit slowly. This suggested the existence of a "working" memory system involved in complex cognitive tasks: an active and complex system for more than the passive storage of information.

1.2. Baddeley's Model of Working Memory

WM, as described by Baddeley and Hitch (1974), was a three-component model in its first conceptualisation. It comprised an attentional control system of limited capacity, called the central executive (CE) and two subsidiary storage systems: the phonological loop (PL), and the visuo-spatial sketchpad (VSSP). This basic model is illustrated in figure 1.2.

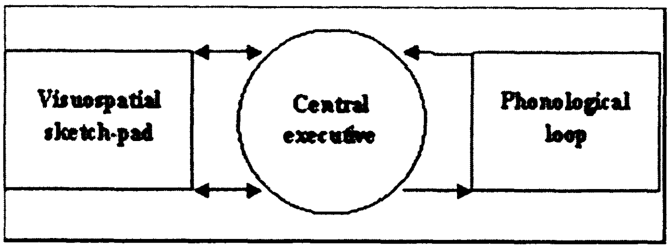

Figure 1. 2. The three-component model of WM (Baddeley & Hitch, 1974)

Later, Baddeley (2000) added a fourth component to the model: the episodic buffer, assumed to be a limited capacity store with multi-dimensional coding that holds and integrates information from a range of systems (such as other WM components and LTM).

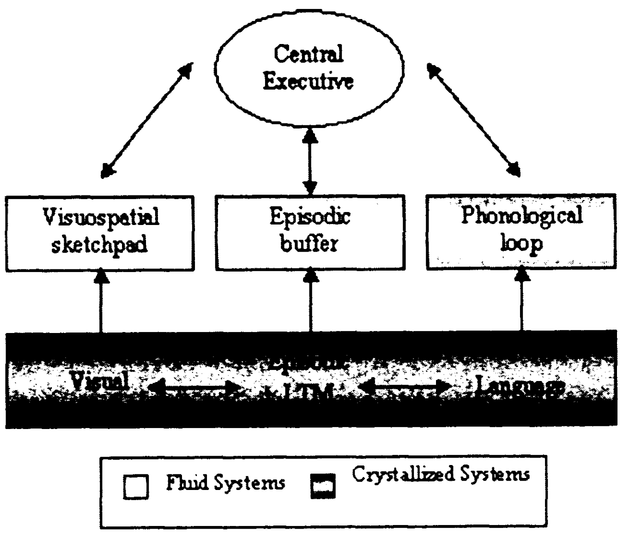

Figure 1. 3: The current multi-component model of WM (Baddeley, 2000)

In the upper part of figure 1.3, "fluid" capacities, such as attention and temporary storage, are shown. In the lower part of figure 1.3, the proposed relation between "fluid" capacities and "crystallized" cognitive systems accumulating long-term knowledge (e.g. language and semantic knowledge) are illustrated.

1.2.1. The phonological loop

As discussed above, one of the findings that led to the concept of a multi-component WM was that participants were capable of holding material (e.g. digits) in STM while concurrently performing complex cognitive tasks (e.g. learning, comprehension, reasoning),with some interference (Baddeley & Hitch, 1974). This finding was not compatible with STM as a unitary store with a capacity of only six or seven items (Miller, 1956), and led to the assumption that the system involved in storing digits was not the same system involved in reasoning, although the two seemed to be connected. This led Baddeley and Hitch (1974) to hypothesise a separate subsystem of WM involved in retaining speech-based material. This phonological loop is controlled by the same central processor responsible for reasoning and learning, but places minimal demands on it. According to this subdivision, patients with STM problems are assumed to have an impaired phonological loop, while the rest of the WM system is spared (Vallar & Baddeley, 1984).

The choice for a speech-based system was motivated by the wealth of evidence suggesting the role of some form of speech code in STM. Moreover, Baddeley and Hitch (1974) assumed that the central processor would be modality free, a hypothesis supported by experiments showing that phonological coding plays a relatively small role in reasoning and comprehension. Baddeley (1986) specified that he used the term "phonological" referring merely to "speech-based" and the term "articulatory" when referring to the subject's speech production system.

The phonological loop is composed of a phonological store, which holds memory traces for a couple of seconds and an articulatory rehearsal process, equivalent to sub-vocal speech. Verbal memory traces can therefore be retrieved through re-articulation. Visual material may be recoded verbally and then it accesses the phonological store through rehearsal (Baddeley, 2003). Most research in this area has investigated immediate serial recall (i.e. the ordered recall of a small set of digits, letters or unrelated words). As articulation takes place in real time, the capacity of this store is limited: with an increase in the number of items to be recalled, there is a point at which the first item fades before having been rehearsed. The role of articulation is supported by the word length effect: when word length increases from one to five syllables, immediate memory span declines. This is thought to be a consequence of the slower rehearsal of longer words. Further support comes from the abolition of this effect when the participant is required to repeat an irrelevant sound and therefore prevented from sub-vocally rehearsing the items to recall (Murray, 1968; Baddeley, Thomson, & Buchanan, 1975; Baddeley, Lewis, & Vallar, 1984b).

Other evidence for the proposed structure of this system comes from neuropsychological patients. Vallar & Baddeley (1984) demonstrated that patients with phonological STM deficits, normal capacity to articulate and no general language impairment, did not show phonological similarity effect (where sequences of letters with similar sound are recalled worse than sequences less similar) nor did they show a word-length effect (where sequences of shorter words are recalled better than sequences of longer words equally frequent in language).

Both these effects are considered "markers" of the phonological loop, which suggests that these patients were avoiding the need to use the impaired phonological store. Moreover, sub-vocal rehearsal was found to be preserved in anarthric patients who are unable to speak because of a deficit in overt articulation, demonstrating that these processes are independent (Baddeley & Wilson, 1985). Conversely, dyspraxic patients who are unable to organise motor programs for internal speech, and therefore to conduct rehearsal, showed a reduction in their memory span (Caplan, Rochon, & Waters, 1992).

As already discussed, the phonological similarity effect and the word length effect support the role of phonological coding in the phonological loop. Further evidence for these and other effects are discussed in the following sections.

1.2.1.1. Phonological similarity effect

Conrad (1964) analysed the errors made when recalling sequences of consonants, and found that the errors tended to be letters phonologically similar to the correct ones (e.g. V would be more likely to be recalled as B than as K), even when the letters were visually presented. This result ruled out the possibility that the error occurred when perceiving the letter, as there was no visually-related error, and suggested that the phonological confusion happened in immediate memory. This was the first convincing evidence that phonological coding is essential in STM. Moreover Conrad and Hull (1964) showed that recall performance was worse when sequences of similarly sounding letters had to be recalled compared to when the letters had different sound. This effect was also evident when recalling words (Baddeley, 1966a; 1966c). In contrast, when long-term learning was required, the phonological similarity became irrelevant while semantic similarity became crucial. The phonological similarity effect in STM has been proved to be very robust (Logie, Della Sala, Laiacona, Chalmers, & Wynn, 1996).

There is debate about whether the phonological similarity effect is due to acoustic or articulatory coding. Convincing evidence for articulatory coding came from a study of congenitally deaf children (Conrad, 1970), showing that some of them (those rated by their teachers as better speakers) were affected by phonological confusion when remembering sequences of consonants. However, this does not exclude the possibility that normal-hearing participants also code information to be kept in STM acoustically.

1.2.1.2. The word-length effect

As mentioned above, Baddeley, Thomson, and Buchanan (1975) realised that sequences of short words were better recalled than those with longer words. In order to ensure that the effect was not produced by linguistic differences (although the words were matched for frequency, the longer words were more complex and had a Latin origin as opposed to the short words being simpler and mostly of Anglo-Saxon origin), the authors replicated the experiment using names of countries (material thought to present fewer differences between short and long items), and found the same result. Another distinction had to be made between duration of the spoken word and length in terms of syllables composing the word. If the relevant variable was the duration of the spoken word, this would argue for a trace decay hypothesis, where a longer word takes longer to be rehearsed and therefore is forgotten more easily. If the length in syllables was the crucial factor, this would argue for an interference theory or displacement model, where STM is a system holding a limited number of memory slots and each slot could contain a fixed number of syllables. Polysyllabic words would overload the system more rapidly than monosyllabic words causing forgetting (Baddeley, 1986).

In order to tease these hypotheses apart, Baddeley et al. (1975) used two sets of bi-syllabic words: one set with brief spoken duration, and the other set with longer spoken duration. They found a tendency for participants to have a better recall on the short-duration words. Studies using different sets of stimuli failed to replicate this finding (Caplan et al., 1992; Lovatt, Avons, & Masterson, 2000), although in these cases there has been debate about whether spoken duration was adequately measured and phonological similarity matched in the two sets (Caplan & Waters, 1994; Baddeley & Andrade, 1994). A study using different sets of stimuli (Service, 1998) has shown the relevance of factors such as phonological complexity over and above articulatory duration, leaving the debate open. A recent study (Mueller, Seymour, Kieras, & Meyer, 2003) has used all the previously employed materials in order to analyse in some depth the roles of phonological similarity and articulatory duration in verbal STM, showing that when similarity and duration are scrupulously measured, both dimensions can account for the results. This allows the possibility that a simple trace decay theory remains useful to explain the word-length effect, without having to investigate a more complex interference theory.

1.2.1.3. Irrelevant (or unattended) speech and irrelevant sound effects

Presentation of irrelevant spoken material concurrently or subsequent to presentation of material to recall, impairs recall performance (Colle, 1980; Salame & Baddeley, 1982; Jones & Macken, 1993; Neath, 2000). This phenomenon was initially interpreted as mnemonic masking in STM (Colle & Welsh, 1976; Salame & Baddeley, 1982), but this interpretation was challenged by the fact that there was no greater effect of irrelevant speech when recalling phonologically similar items (Salame & Baddeley, 1986) nor when the irrelevant material was similar to the material to be recalled (Jones & Macken, 1995; Le Compte & Shaibe, 1997; Larsen, Baddeley, & Andrade, 2000). In addition to concurrent irrelevant speech disrupting recall performance, music and variable tones in general also cause impairment in recall (Jones, Beaman, & Macken, 1996).

1.2.1.4 Articulatory Suppression

Another effect that has been integral to the conceptualisation of a phonological loop is that preventing articulatory rehearsal of items by requiring the participant to articulate an irrelevant sound (e.g. repeating "the") impairs immediate serial recall (Baddeley et al., 1984b). Articulatory suppression also interacts with the aforementioned effects. Suppression removes the effect of phonological similarity with visual presentation because it interferes with sub-vocal articulation which enables the translation of visually presented material into phonological material. When the material to be recalled is auditorily presented, instead, it gains immediate access to the phonological store with no need for the mediation of sub-vocal articulation. Therefore, suppression does not remove the phonological similarity effect. Similarly, when the material to be recalled is visually presented, articulatory suppression removes the effect of unattended speech because it prevents the material from being registered in the phonological store. Unattended speech is therefore not relevant because although it is impairing the correct functioning of the phonological store, this store is not involved in the memory task because visual material has been prevented from being registered phonologically in it by articulatory suppression. When the material is auditorily presented, articulatory suppression does not remove the effect of unattended speech. The effect of articulatory suppression on the word-length effect is slightly different: with both visual and auditory presentation, the articulatory suppression removes the word-length effect because the influence of word length only operates through sub-vocal rehearsal.

1.2.1.5 Functions of the Phonological Loop

Baddeley, Gathercole and Papagno (1998b) studied a patient with a specific deficit of the phonological loop who was unable to learn the vocabulary of a new language but had unimpaired verbal LTM. The authors therefore suggested that the function of the phonological loop is to facilitate the acquisition of language. Further evidence supporting this hypothesis came from the fact that articulatory suppression, phonological similarity and word length (that, as discussed above, all disrupt the functioning of the phonological loop) disrupt the acquisition of foreign words but not the acquisition of pairs of unrelated words of the native language (usually based on semantic coding) (Papagno, Valentine, & Baddeley, 1991; Papagno & Vallar, 1992). Moreover the capacity of the phonological loop has been found to be a good predictor of the ability of adults (Atkins & Baddeley, 1998) and children (Service, 1992) to learn a second language.

According to Baddeley et al. (1998b), the phonological loop primarily evolved to facilitate the acquisition of native language. Evidence supporting this view came from studies showing that a good predictor of vocabulary acquisition in children is non-word repetition, which is dependent on the phonological loop

(Gathercole & Baddeley, 1989; Gathercole & Adams, 1994). Furthermore, there are studies demonstrating that children with specific language disability (in absence of hearing or articulatory problems) and normal non-verbal intelligence, show poor performance on non-word repetition (Gathercole & Baddeley, 1990).

Baddeley (2003) argues that the phonological loop facilitates language acquisition in two ways: the phonological store provides temporary representation for new phoneme sequences, and the articulatory output component facilitates learning through rehearsal if the new sounds are representable using output processes already present. Some evidence supporting this conceptualisation comes from studies showing that spoken recall of words was better than recall of non-words, but that there was no difference in recognition of words and non-words (Gathercole, Pickering, Hall, & Peaker, 2001; Thorn, Gathercole, & Prankish, 2002). These results demonstrated that previous language habits (in the case of words) influence performance requiring the articulatory output component of the phonological loop but not the storage component, that appears to be rather language independent.

1.2.2. The visuospatial sketchpad

The visuo-spatial sketchpad is a system that holds and manipulates material of a visual or spatial nature.

Initial work on this area was done by Baddeley, Grant, Wight and Thomson (1975) who used the dual task in order to understand what processes were involved in visual imagery. The authors found that spatial tasks performed concurrently with a visual imagery task have the effect of suppressing the visual image. They also found that this system was involved in visual imagery used to help memorise verbal material, but not in the recall advantage for highly imageable phrases compared to less imageable ones (effect that was found by Atwood (1971)).

Initial studies of visuo-spatial STM seemed to focus more on visual than spatial aspects. More recent investigations suggest, instead, that the visuo-spatial sketchpad comprises separate components for visual and spatial items. The task used to measure spatial span is the Corsi block tapping test: the experimenter taps a certain sequence within the nine blocks available and the participant has to reproduce the sequence (Corsi, 1972). As with verbal span, the sequence gradually increases until the participant fails to reproduce correctly the sequence. The pattern span is the visual non-spatial analogue of the previous, where the participant has to recall which cells of a previously presented matrix were filled (Della Sala, Gray, Baddeley, Allamano, & Wilson, 1999). Once again the matrix size increases gradually until the performance breaks down. Della Sala et al. (1999) found a double dissociation between spatial and visual span: the Corsi task in healthy participants is disrupted by spatial interference more than by visual interference and the reverse can be found for the pattern span. Additional evidence of the separation of visual and spatial STM come from neuropsychological patients showing dissociations between visual and spatial STM (Della Sala & Logie, 2002). Different authors have proposed different characterisations of the components of the visuo-spatial sketchpad in terms of: spatial ("where" visual path) and object ("what" visual path) coding (Mishkin, Ungerleider, & Macko, 1983; Smith, 1995); dynamic (spatial) and static (pattern) coding (Pickering, 2001); and the addition of a motor dimension of coding (Smyth & Pendleton, 1990).

Further studies are needed in this area in order to discriminate the possible components of this store.

1.2.3. The central executive

In the original model of WM (Baddeley & Hitch, 1974) the Central Executive (CE) was considered as a pool of general processing capacity, and anything that could not be explained by the two sub-systems (PL and VSSP) was assigned to it. The concept of a storage capacity of the central executive (i.e. the above mentioned concept of "processing capacity") was later abandoned by Baddeley (1993) and it will be discussed in paragraph 1.3. when describing an alternative framework that has been used to conceptualise WM (Cowan, 1995; 1999; 2001; 2003; 2004; 2005). Baddeley (1986) suggested adopting the Supervisory Attentional System (SAS) model of attentional control by Norman and Shallice (1986) as a way to conceptualise the CE. The SAS model explains attentional control in two ways: with a routine control, by habitual patterns or schemas, guided by cues from the environment; and with the SAS that is an attentionally limited controller, intervening when the routine controller is not enough. Evidence supporting this model came from slips of action in everyday life and from the study of patients with frontal lobe damage resulting in failure to inhibit prepotent responses, perseveration and distractibility. Baddeley (1996) attempted to analyse the component functions of the Central Executive, suggesting that the capacities needed by it, as an attentional controller, were to coordinate performance on two separate tasks (e.g. in dual task), to switch retrieval strategies (e.g. in random generation), to attend selectively to one stimulus while inhibiting others (e.g. in selective attention), and to hold and manipulate information in LTM (e.g. in WM span).

1.2.3.1. *Dual-Task Performance*

In order to test the ability to coordinate performance on two separate tasks, Baddeley, Logie, Bressi, Della Sala, and Spinnler (1986) set up a number of tests to assess the two slave systems of WM separately (articulatory suppression, reaction time to a tone and auditory digit span for the phonological loop and visuo-motor tracking for the visuo-spatial sketchpad). The authors decided to study the performance of patients with Alzheimer's disease as there was evidence of these patients being impaired in both verbal and visuo-spatial WM, compared to that of normal elderly and young control participants (Spinnler, Della Sala, Bandera, & Baddeley, 1988). The groups were first tested on individual tasks and then on two tasks combined. The level of performance on the individual tasks varied between groups so that the error level was the same across participants. The results showed that the performance of the patient group significantly decreased in the dual task condition compared to the two control groups, supporting the hypothesis that the ability to combine performance on two tasks (arguably a necessary function of the CE) is particularly impaired in AD patients. This explanation seems to be more plausible than alternative ones, such as a decline in the constituent peripheral tasks or an overall cognitive deficit (e.g. a reduction of general intelligence found with ageing (Rabbitt, 1983)), because this effect was specific of AD and not found in the group of elderly controls. Another study (Della Sala, Baddeley, Papagno, & Spinnler, 1996) showed that neurological patients with frontal lobe lesions and disinhibited behaviour showed a decrement in performance on a dual task (box-crossing and digit span) compared to frontal patients without behavioural disorder. This might suggest that disinhibited behaviour that can be found in frontal lobe patients is linked with difficulty in distributing attention.

1.2.3.2. Random Generation

Switch retrieval strategies were studied as another area of investigation of executive function in order to explain a set of results suggesting that generating sequences of letters as randomly as possible was dependent on a limited-capacity system (Baddeley, 1966b). Results had in fact shown that the faster the rate, the less random was the output. When random generation was performed concurrently with a card sorting task, as the number of sorting alternatives increased, the sequence of letters generated was less random. The Norman and Shallice model (1986) allowed an interpretation of these results. Performance on the random generation task required the retrieval of a series of habitual letter-retrieval schemata (based for example on the alphabet or the production of common acronyms) and the intervention of the SAS in order to break the usual sequences. Since the SAS was also required for the card-sorting task, this interfered with the random generation of letters (Baddeley, 1986). Using the random generation task without verbal output (random key-pressing), Baddeley, Emslie, Kolodny, and Duncan (1998a) showed interference on a verbal memory task (span task with sequences of lengths ranging from 1 to 8), suggesting that performance depends on a general purpose system. They also showed that the degree of disruption in the random generation task was greater with concurrent memory load, suggesting a limited-capacity WM. The authors continued investigating how various tasks with different expected loading on the CE influenced random keyboard generation. They found that, as expected, the less dependent the task was on executive resources, the less impact it had on random generation. Articulatory suppression (e.g. counting repeatedly from 1 to 6) had no significant effect on random generation. Category generation (i.e. generating as many items as possible from a specified semantic category), a verbal fluency task believed to depend heavily on executive resources because very sensitive to concurrent digit span (Baddeley, Lewis, Eldridge, & Thomson, 1984a) and to dysexecutive syndrome, significantly disrupted performance on random generation. Finally, the AH3 test, a measure of general reasoning considered a measure of fluid intelligence (Heim, 1975) and arguably an index of executive function depending upon the functioning of the frontal lobes (Duncan, 1993), had an even heavier effect on random generation. This set of results confirmed the assumption that random generation and tasks dependent on CE functioning compete for the same limited capacity. In order to address the possible underlying processes of a random generation tasks, the authors used a model similar to Roediger's (1993) simplified version of the SAM model of Raaijmakers and Shiffrin (1981). According to this model, during random generation a retrieval plan is set up, then run, and then the output is checked and released if judged to be properly random. The authors assumed that a decrease in randomness at higher speeds was attributable to the time taken to shift between retrieval plans. If there was no time pressure, there would be no need to check for the randomness of the output as the participant could switch every time. If, on the other hand, the same retrieval plan was repeatedly used, the responses would unlikely be random. Therefore a concurrent activity interfering with the capacity to switch retrieval plans will decrease the degree of randomness. The effect, far from being catastrophic, is that the person makes fewer switches of retrieval plan and therefore produces more stereotyped responses. This model explained the results found by Baddeley et al. (1998a) when they asked their participants to simultaneously perform random number generation and random key-pressing both at a 1/second rate: there was a reduction in randomness but the performance was not totally disrupted.

In order to test the switching hypothesis directly, the authors conducted two more experiments where participants were asked to press keys at a rate of 1/sec, either alone or in conjunction with one of three concurrent tasks: reciting the alphabet at the rate of 1/sec, counting at the rate of 1/sec, or alternating letters and numbers (the verbal equivalent of the Trails Test B where participants are required to alternately connect letters and numbers in order – e.g. A-1-B-2-C-3, etc.-, a test sensitive to frontal lobe damage (Lezak, 2004)). In both experiments only the concurrent alternation task reduced randomness, despite the minimal memory load and its predictability. In the second experiment the whole task was disrupted (generation stopped and the participant had to be prompted by the examiner in order to continue). The authors therefore suggested that both random generation and the simple alternation task disrupt the functioning of the CE because of their demand for continuous switching of retrieval plans. Despite Baddeley et al.'s (1998a) model of random generation can explain their results, the authors acknowledge that it fails to clarify whether the load imposed by the task results from the need to switch strategies, a difficulty in accessing new strategies, or the process of checking on the response output. Also, the idea of a general processor with limited capacity responsible for both input and retrieval may be an over-simplification. In fact, in a study of the effects of a concurrent sorting task on word list learning and on retrieval, Baddeley et al. (1984a) found that the sorting task markedly affected learning but there was no effect on retrieval.

Craik and colleagues (Craik, Govoni, Naveh-Benjamin, & Anderson, 1996; Naveh-Benjamin, Craik, Gavrilescu, & Anderson, 2000) focused on the role of attention: they found that dividing attention during encoding reduced accuracy in recall, whereas dividing attention during retrieval produced little or no effect. This result suggests that retrieval does not recapitulate encoding, as previously suggested by Craik (1983) and by recent neuroimaging studies showing that encoding and successful retrieval are associated with heightened activity in the same cortical areas (Roediger, Gallo, & Geraci, 2002). The authors (Craik et al., 1996; Naveh-Benjamin et al., 2000) suggested that the observed differences between encoding and retrieval were not necessarily in contrast with findings and theories stressing the similarities between these two processes. Their working assumption was that the differences were related to the different control processes associated with encoding and retrieval, whereas previous studies focused on the actual representations themselves (e.g. investigating encoding specificity, transfer appropriate processing and repetition of operations). The authors also suggested that the distinction between different control processes for encoding, retrieval and accessing the representations themselves is supported by neuroimaging findings. In fact there is good evidence, as mentioned above, that encoding and retrieval activate the same cortical areas (Squire, Cohen, & Nadel, 1984; Mishkin & Appenzeller, 1987; Nyberg, Tulving, Habib, Nilsson, Kapur, Houle, Cabeza, & McIntosh, 1995; Wagner, Poldrack, Eldridge, Desmond, Glover, & Gabrieli, 1998; Roediger et al., 2002). Naveh-Benjamin et al. (2000) interpreted this data as a reflection of the crucial similarity between encoding and retrieval processes for the initial setting up of, and later access to, the representations themselves. The authors also reported neuroimaging data supporting the differential involvement of the left and right frontal lobes during encoding and retrieval respectively, and they suggest that this difference could be due to the different control processes involved (Nyberg, Cabeza, & Tulving, 1996; Cabeza & Nyberg, 1997).

The interpretation of the results of Craik and colleagues (Craik et al., 1996; Naveh-Benjamin et al., 2000) is tentative because they showed single dissociations that may reflect quantitative differences in sensitivity and not necessarily qualitative differences in processing (Naveh-Benjamin et al., 2000). Moreover, other studies have found that dividing attention during retrieval affects memory accuracy (Hicks & Marsh, 2000; Rohrer & Pashler, 2003).

In conclusion, much has still to be understood about the role of attentional processes in retrieval and further research is needed in this area.

1.2.3.3. Selective attention

In Baddeley's (1996) concept of a general executive processing system, there is a third component in addition to the previously described capacity to timeshare and switch retrieval plans: the capacity to selectively attend to one source of information and to ignore others (i.e. selective attention). Most of the studies he describes that have been carried out to investigate this have involved middle-aged and elderly participants or patients with Dementia of the Alzheimer's type (DAT) on the assumption that age and presence of a cognitive degeneration such as that involved in DAT, are variables that affect executive processes. For this reason, these studies will be addressed in the section on the effects of ageing (see par. 3.1.) and of DAT (see par. 4.1.1.) on WM.

1.2.3.4. Working Memory and Long Term Memory

Another characteristic that Baddeley (1996) suggests the CE has is to be able to temporarily activate LTM. He reports the case of a patient, KJ, with normal intelligence and pure amnesic syndrome who was able to immediately recall a brief story presented to him, but could not remember anything about the story (not even that he had heard one) half an hour later (Wilson & Baddeley, 1988; Baddeley & Wilson, 2002). In order to explain how he could initially recall the story, Baddeley (1996) uses the idea that comprehension entails the construction of a mental model (Johnson-Laird, 1983), and suggests that this mental model in turn demands WM capacity. This capacity is unlikely to be limited to the functioning of the two slave systems, because they would probably not be able to reflect the semantic complexity and application of previous learning involved in comprehension. It seems more likely that these mental models correspond to the temporary activation of components of LTM. This idea has been investigated by Ericsson and Kintsch (1995) with studies of prose comprehension and the performance of mnemonic experts. The authors suggest that a model of WM should include a mechanism that they call "long-term WM". When reading, a representation of the sentence is generated in short-term WM, but sentences are also linked to previously constructed representations of the text and to the previous knowledge of the reader. These links produce a long-term WM representation that enables the reader to have access to the most relevant parts of the representation of the sentence held in short-term WM, as Butterworth, Shallice and Watson (1990) had earlier suggested. Some evidence for the existence of this system comes from studies of reading comprehension. For example a participant can stop reading for more than 30 seconds without consequences on comprehension. Moreover, after the interruption there is an initial increase in reading times, possibly due to the time taken to retrieve the structure of the sentence from long-term WM and to reactivate the information held in short-term WM before the interruption (Ericsson & Kintsch, 1995). The idea of WM as temporary activation of selected representations in LTM had also been addressed by Adams and Gathercole (1995), who noticed how memory span for non-words phonotactically similar to English words is higher than for non-words dissimilar to English words, and suggested that PL is a system that has developed based on previous phonological experience.

The CE is a possible way of conceptualising a hypothetical general retrieval system involved in encoding and retrieving information from both the slave systems and temporarily activated components of LTM.

Studies along these lines came from Daneman and Carpenter's (1980) introduction of a measure of WM as a system for processing and storing information, that they called Working Memory span. This task involves presenting participants with a series of sentences to process (by deciding whether they are true or false) and from which to remember the last word. At the end of the series participants are asked to recall the last word of each sentence. The WM span is the maximum number of sentences that the participant can process while retaining the last word. This measure is usually between two and five. A problem that emerged from the results was how to explain individual differences in WM span that seemed to impact on other complex cognitive functions.

Cantor and Engle (1993) suggested that participants with a high WM span were able to activate more information from LTM (where WM is seen as reflecting the activation of various amounts of information stored in LTM). The authors used the "fan effect" (i.e. the fact that to verify a statement takes longer if the subject/object of the statement has been linked to various other statements) to investigate this idea (Anderson, 1974). Anderson explains the effect as a result of the limited amount of activation spreading from each unit of the sentence to its associated features. According to Cantor and Engle (1993), participants with high WM span would have more potential activation. This was confirmed by the fact that participants with a low WM span took comparatively longer to verify sentences when the set size was bigger. Conway and Engle (1994) linked the fan effect with Sternberg's (1966) finding that there is a linear relationship between the time taken to decide if an item was presented previously, and set size. In Conway and Engle's experiment, participants learn sets of letters of various lengths (two, four, six or eight letters) and are then asked to decide whether a probe letter was part of a particular group. The more items in the group, the more time it took the participants to answer, with this effect being stronger in the low-working-memory-span participants. By delaying the presentation of the probe letter and specifying the set first, the authors were able to distinguish between the time taken to access a given set and the time to verify the presence of the probe letter. They found that only the time taken to check for the presence of the probe was influenced by WM span, and concluded that accessing the set of letters is a relatively automatic process and does not depend on WM, whereas verifying the presence of a probe involves an active search process dependent on the limited-capacity system. So far it would seem plausible to conclude that individual differences in WM might depend on the activation available.

Engle (1996) however, reported some results that are not compatible with this idea: when a category-generation task was combined with a concurrent attention-demanding task (e.g. learning a subset of items to exclude from the generation task), this reduced the performance of participants with high WM span, but not of participants with low WM span (even if the items to exclude were of a category unrelated to the generation category). These results suggest that WM span allows participants to be distinguished on the basis of the strategies they use rather than continuously varying processing capacity per se. Another set of results that are difficult to explain using a model where individual differences in WM are dependent on the amount of activation available, are those reported in Cantor and Engle's (1993) study previously described, where some of the letters were repeated in different sets. Engle (1996) tried to replicate the findings using sets where letters were not repeated and failed to find the same difference between participants with high and low WM span. Engle modified his original model to one more similar to the concept of CE (Baddeley & Hitch, 1974) where the capacity to inhibit irrelevant information is of crucial importance. This idea is consistent with findings on ageing and WM (Hasher & Zacks, 1988).

1.2.4. The Episodic Buffer

Although the original WM model (Baddeley & Hitch, 1974) was able to account for much of the empirical evidence, a number of findings were not accounted for in a satisfactory way.

As discussed above, the model could not explain how the subsystems of WM related to LTM, even if there was evidence that measures of WM were affected by variables considered to be related to LTM, such as word frequency and imageability (Hulme, Roodenrys, Brown, & Merver, 1995). Moreover, as discussed above, the model did not satisfactorily account for the findings of individual differences in WM span (Daneman & Carpenter, 1980; 1983).

The WM model was not able to explain why a meaningful relationship between words to be recalled was an advantage (Baddeley, Vallar, & Wilson, 1987) nor to explain the process of chunking, where individual items are aggregated in larger units (Miller, 1956).

Furthermore, the model also failed to explain how information from the two slave subsystems - supposed to be separate and independent - could be combined as shown by the finding that simple verbal span could combine verbal and visual encoding (Chincotta, Underwood, Abd Ghani, Papadopoulou, & Wresinksi, 1999).

It seems clear that the original model of WM (Baddeley & Hitch, 1974) is not able to account for the ability to integrate and store information from various sources, including the slave systems and LTM so that information can be actively maintained and manipulated. Therefore, it seems useful to add a fourth component to the original model that better accounted for these findings and the more complex aspects of executive control (Baddeley, 2000). The episodic buffer was therefore conceived as a limited capacity system for the temporary storage of information in multimodal code (Baddeley, 2000). This buffer is able to combine information from the two slave systems and from LTM, into a unitary representation. Information is retrieved from this buffer through conscious awareness.

Repovs and Baddeley (2006) suggested that in order to investigate this buffer and evaluate its role in cognition, measures of capacity and interference should be developed. Prabhakaran, Narayanan, Zhao, and Gabrieli (2000) used a task requiring the participant to remember letters and locations while in a fMRI scanner. The authors found that when the letters and the locations were connected (with each letter representing a location), accuracy was higher and reaction times were shorter, compared to when letters and locations were not connected. Moreover, when the probe letter at recall was presented in the same position as at presentation, accuracy was higher and reaction times shorter, compared to when the probe was presented in a different location. The authors also found that in the condition combining letters and locations, there was right prefrontal activation. They therefore suggested the presence of a separate memory buffer, distinct from the phonological loop and the visuo-spatial sketchpad, and responsible for the temporary retention of integrated information from the two sub-systems. Zhang, Zhang, Sun, Li, He, & Hu (2004) used a similar task and replicated Prabhakaran et al.'s (2000) findings.

The empirical evidence to support the existence of the episodic buffer, maintaining and integrating information from other systems, is still sparse due to the recent conception of this addition to the WM model.

1.3. An "Embedded Processes" model of Working Memory

Nelson Cowan (1988) suggested that within the field of WM, there is at times some confusion over terminology: in particular, he claimed that it was sometimes difficult to know whether the concept of WM was used with reference to what he referred to as "activation" or to the "consciously available portion of memory and thought" (Cowan, 2005). This is particularly relevant when considering the Central Executive component of Baddeley's model and the concepts of control processes and processing capacity (Baddeley, 1986). As mentioned previously, Baddeley initially made such a distinction but later abandoned the concept of a storage capacity of the central executive (Baddeley, 1993). This leaves some confusion over the limits of the Central Executive, in terms of the amount of information that can be manipulated at any one time. It is unclear whether this depends on the "consciously available portion of memory and thought" or on the "activation" itself, and whether the relationship between these is conceptualised and studied. Cowan (1999) argued for the importance of a distinction between the "focus of attention and awareness" and "the sum of activated information", and suggested that WM involves both activation and awareness (as well as LTM information). This concept is similar to Broadbent's (1958) idea of a limited-capacity channel, where only selected information can be subject to attentive analysis by the system, thereby avoiding the processing of irrelevant information. Also in Broadbent's (1958) view a distinction can be drawn between the limited content that is allowed into the channel and the process of attentive analysis.

Cowan proposed a framework offering a functional definition of WM where the processing mechanisms that contribute to a memory task are considered to collectively make up WM. This model is obviously different to frameworks where WM is defined according to the processing mechanisms themselves (e.g. Baddeley's model). The distinction made by Cowan between his own description of WM as a set of processes that hold a limited amount of information in a state readily accessible for an active task, and Baddeley's explicit description of a multifaceted system, is reflected in Cowan's search for a more general level of analysis as opposed to a discrete buffer-identification strategy (Cowan, 2005). Cowan compares his and Baddeley's approaches using an analogy of a house that has only been examined from the outside: Baddeley's approach would be represented by making very detailed predictions on the rooms and their sizes (e.g. hypothesising that there is a kitchen, a bathroom, two bedrooms of the same size and a living room), whereas Cowan's approach would be making exhaustive predictions but less committed to detail (e.g. hypothesising the presence of food preparation quarters, sleeping quarters, bathroom/toilet quarters and other living quarters (Cowan, 1988; 1995; 1999). Of course Cowan's approach might overlook important distinctions within the WM system, but he argues that there may be only subtle distinctions between a view based on distinct buffers and his own more integrated approach (Cowan, 2005).

Cowan's model of WM is an "embedded processes" model and it distinguishes between two components of the processing system: the subset of elements represented in memory that are in a temporarily heightened state of activation, and a smaller subset of activated memory that is in the focus of attention (Cowan, 1988; 1999). More specifically, his model consists of central executive processes, LTM, active memory, and attentional focus. Active memory is considered to be a subset of LTM and the focus of attention a subset of active memory. The direction of the attentional focus is controlled by the Central Executive. In Cowan's view, during a task some information would be in the focus of attention, some in an activated state, ready to enter the focus of attention if required, and some may simply be inactive. Inactive information could be quickly made available from long term-memory, if required. Cowan also describes the limits of the WM system: memory activation is time-limited and fades within about 10 to 20 seconds unless it is reactivated, whereas the focus of attention is has a limited capacity of about four unrelated items, although chunking could raise this limit (Cowan, 1999; 2001). He also suggests that only the information in the focus of attention is available to conscious awareness and report (Cowan 2001). If information exceeds the capacity of the focus of attention, the earlier items in the focus have a higher chance of being deactivated and displaced from the focus of attention (Haarmann & Usher, 2001).

The activated elements in memory and the focus of attention in Cowan's (1995) model roughly correspond to the passive store (PL) and the storage capacity of the CE (Baddeley, 1986) (concept later abandoned by Baddeley (1993)). Cowan (1999) conceptualised Baddeley's articulatory control as a type of memory reactivation process, where subvocal rehearsal reactivates information by recirculating it through the focus of attention, and memory reactivation routines are initiated by the central executive. Moreover, according to Cowan (2005), the focus of attention is in part controlled by CE processes. Therefore, Baddeley's and Cowan's models are not incompatible, despite the differences between their approaches to the conceptualisation of WM, as suggested by Baddeley (2003) himself. As far as this dissertation is concerned, what is useful from Cowan's (2005) conceptualisation, is the idea of a focus of attention that can play a role in both storage and processing.

1.4. Updating and Inhibition in Working Memory

From the evidence reported in the preceding discussion, it appears quite clear that the role of WM in complex cognitive functions (such as reading comprehension) may be related to the general resources available to the system, conceptualised as long-term WM by Ericsson and Kintsch (1995) and as Episodic Buffer by Baddeley (2000). Although the empirical evidence is considerable, there remains little agreement theoretically. Moreover, another line of research has shown that a poor performance can be due to poor ability to use resources (e.g. poor use of strategies), rather than a deficit in resources per se. Inhibition is one such strategy that concerns the reduction or suppression of the activation associated with a certain information, when it is no longer useful. Many cognitive processes are sensitive to interference effects when the participant fails to inhibit similar or concurrently presented materials appropriately (Dempster & Brainerd, 2006). Therefore, the ability to inhibit information that is not relevant to the task is essential for good performance (Engle, 1996).

There are several distinctive uses of the term inhibition in the literature: it can refer to information irrelevant to the task from the very beginning (inhibition), for example in the case of priming; and to information that is initially relevant but becomes irrelevant when proceeding on the task (suppression). Another distinction to be made is the origin of the material to inhibit, as it can be retrieved from LTM or it can be material that has just been processed by the participant. One example of inhibition of information retrieved from LTM is Conway and Engle's (1994) experiment described earlier, which suggests that what distinguishes participants with high and low WM span is the ability to inhibit irrelevant information. Therefore, the ability to manage the activation of information leads to differential WM performance. The authors also suggest that it cannot be determined whether this lack of inhibition is due to a generalised lack of resources to use for this purpose. In order to support this hypothesis Conway, Tuholski, Shisler,and Engle (1999) studied the effect of a verbal and a nonverbal memory load on negative priming. The authors asked participants to perform a letter naming task with a concurrent memory task. Negative priming occurred only when there was no memory load, independently of type of load (i.e. verbal/non-verbal), suggesting that the processes involved in negative priming are dependent on a general and multi-modal resource pool. The authors also observed individual differences in negative priming and suggested that this resulted from the allocation of controlled attention and the differential ability to efficiently inhibit irrelevant information.

Coupled with the idea of inhibiting irrelevant information is the concept of selecting and updating the relevant information needed to perform tasks. This ability is essential for good performance on many complex cognitive tasks. Morris and Jones (1990) devised a task to measure this aspect, based on the test of running memory span developed by Pollack, Johnson and Knaft (1959). The key feature of this kind of span task is that the participant has to retain a defined number of items from a list presented to them without knowing at which point in the list they will be asked to recall the items. The idea behind this task is that participants need to leave out old items and capture new items in order to perform efficiently. Morris and Jones (1990) presented their participants with sequences of letters of lengths from four to ten and asked them to recall the last four or the last six items (the latter being a memory load close to or beyond the span of participants) of each list. As the length of each sequence was not known by the participant, each item had to be initially retained and updated as the presentation continued. The authors aimed to distinguish between demands on the articulatory loop and CE, hypothesising that the latter would be the system responsible for updating. In order to test this hypothesis, authors examined the effects of articulatory suppression and irrelevant speech on running memory. They suggested that if memory updating required resources from the central executive but not from the phonological loop, and if serial recall required resources from the phonological loop but not from the central executive, then one should expect main effects of both number of updates (i.e. each time the participant has to drop one item he had to initially retain) and secondary task (disrupting the phonological loop), but no interaction between the two. In support of their hypothesis, the authors found that articulatory suppression and irrelevant speech impaired serial recall but not the updating component of the task. Therefore they suggested that memory updating is not performed by the articulatory loop and is independent of memory load. Another interesting finding was that whereas the act of updating had an impact on performance, the number of updates had no effect. This may mean that the central executive is either able to perform several subsequent updates without overloading its capacity, or it has a very fast rate of recovery. One possible way in which updating may be achieved is by relying on passive storage: the most recent items would over-write earlier items and the final set would be rehearsed by sub-vocal articulation, and items not rehearsed would be forgotten when they are replaced. Passive storage was proposed by Baddeley (1986) as a way of explaining recency effects, and he argued that information in the system would constantly be modified and updated. In Morris and Jones' (1990) experiment, though, the effect of the secondary tasks suggests that most of the items were rehearsed by means of the articulatory loop. Therefore, it remains unclear how the set to be rehearsed is updated by participants as they are constantly required to change the rehearsed set after each item added to the list. The idea of a passive storage struggles to account for this constant shift and it is likely that an executive mechanism is required. The central executive may therefore be the system responsible for updating, by acting as a supervisor that selects strategies and integrates multiple sources of information. Kiss, Pisio, Francois and Schopflocher (1998) recorded visual event-related brain potentials (ERPs) during a running memory task and a control task, and found that the different ERPs obtained by subtracting performance on the latter from the former reflected processing control as opposed to storage. The authors suggested that their findings are consistent both with Baddeley's (1986) WM model (postulating separate storage and control modules) and with Morris and Jones' (1990) claim that the Central Executive is the system responsible for memory updating.

1.5. WM and Complex Cognitive Functions

Baddeley and Hitch (1974) multi-component model of WM was conceived as the basis for complex cognitive abilities. In particular they identified mental arithmetic and reading as possible applications of the WM concept (Baddeley & Hitch, 1977). Concerning arithmetic, the authors described a series of studies investigating errors in the addition of pairs of numbers of two or three digits. Although different people use different information processing strategies, almost all of these strategies consisted of sequences of simpler arithmetical steps. An example of a sequence of steps could be the person retrieving starting information from working storage, transforming it by using long-term knowledge of arithmetical facts and rules, and either holding this intermediate information in working storage for a later operation or produce a result. Hitch (1978) found that forgetting information held in WM was a major source of error.

Baddeley and Hitch (1977) also suggested that the WM system could be a useful framework to study reading. WM span (Daneman & Carpenter, 1980) has been used to study reading comprehension (Just & Carpenter, 1992). This measure also seems to correlate highly with scores on standard intelligence tests (Kyllonen & Christal, 1990). This finding suggests that the measure reflects some process, but what this process is remains a controversial topic. An initial debate around this task concerned whether the WM system probed in Daneman and Carpenter's (1980) span task is limited to language processing or reflects a broader system. Evidence for the latter hypothesis came from a study by Turner and Engle (1989) who found the same effects on WM span when using either arithmetic operations or sentence verification. This hypothesis is also consistent with findings of individual differences in WM span (Shute, 1991) and with Baddeley et al.'s (1998a) results on random generation.

De Beni, Palladino, Pazzaglia and Cornoldi (1998) suggested that an inhibition deficit in poor readers leads to an overload in WM which affects comprehension. They showed that poor readers had a shorter WM span than good readers and that they produced more intrusion errors, taken in this study as a measure of difficulty in inhibition (although the possibility that they are due to a deficit in semantic processing or in resources available can not be excluded). It would therefore seem that a deficit in the inhibitory process leads to poor performance in WM tasks and comprehension. Besides the ability to inhibit the information that is irrelevant, another key feature of successful comprehension is the ability to select the most relevant parts of a text and to remember the information that is useful for understanding the following parts (Brown, Armbruster, & Baker, 1986; Garner, 1987). The information kept in WM needs to be constantly updated, however, to ensure it does not exceed the capacity of the system. Palladino, Cornoldi, De Beni and Pazzaglia (2001) studied the relationship between reading comprehension and updating in WM. They compared groups of good and poor comprehenders in several tasks of updating, because they allow the simultaneous measurement of maintenance and updating of information. The original test was designed to measure the Central Executive (Morris & Jones, 1990) and was inspired by the running memory span test (Pollack, Johnson, & Knaft, 1959). The authors adapted it using words instead of letters (Palladino et al., 2001). They found that the ability to update was worse with longer series of words, and in poor comprehenders. To make the task more similar to the actual process of comprehension, the participants were presented with lists of nouns referring to items of different sizes and were asked to remember a certain pre-defined number of the smallest items presented. In this task poor comprehenders remembered fewer items and made more intrusion errors. In two further experiments the authors manipulated memory load (i.e. the number of items to recall) and suppression demand (i.e. the number of items that could be relevant) and found that both impaired performance. Poor comprehenders made more intrusion errors, particularly when there were more demands on suppression. When participants were asked to specify the size of presented items, the recall of poor comprehenders was low but they did not make intrusion errors, therefore they could select the appropriate item. The authors concluded that there is a relationship between reading comprehension and WM abilities.

1.5.1. Working Memory and Calculation

Mental calculation is a multi-component process and every stage is essential for correct performance. Whereas simple arithmetic problems (e.g. 4 X 5) can be solved by retrieving the answer from memory, and do not require actual computation (Ashcraft, 1992; Campbell, 1995), more complex operations (e.g. 43 X 12) require the use of computation. This involves holding and manipulating numbers in STM while the appropriate algorithm to solve the problem is applied.

The application of the algorithm is in itself a complex process that involves various steps to be followed in the appropriate sequence. It also requires the retrieval and short term storage of intermediate results that will have to be forgotten after being used as well as the application of arithmetical rules. This process therefore requires attentional control and WM processes such as updating (Baddeley, 1986).

The concept of WM has provided a framework for investigating mental arithmetic (Baddeley & Hitch, 1977). Using the idea that in performing mental arithmetic one must use well-learned strategies which involve the temporary storage of information, the authors investigated this complex cognitive task. In a series of experiments they examined in some detail the kind of errors made when adding pairs of numbers of two or three digits. They found that despite the use of different processing strategies by different people, all the strategies consisted of sequences of elementary arithmetical steps, showing a close interplay between information processing and temporary storage, in accordance with the concept of WM. For example, a typical strategy they observed can be subdivided into several steps: retrieving the problem to be solved from working storage; performing the arithmetical transformation (using knowledge stored in LTM); using the result as an output; or holding it in "working storage" to use it as part of some later operation. In written calculation, the page on which the person writes is used as a permanent working store, which substitutes the human working storage (Lindsay & Norman, 1972). These authors suggest that overflow of storage capacity is a critical source of errors in mental calculation.

Hitch (1978) further investigated the idea that some form of memory storage takes place during the stages of performing mental addition. His idea was that interim information produced in the course of computation would be forgotten if not immediately used. He found support for this hypothesis, showing that people perform complex mental calculations by subdividing them into elementary stages. Errors arise because initial and interim information are held in working storage where they are subject to decay. One implication of Hitch's decay model concerns the presence of a "carry" to be held from a previous stage to be used later. It seems that participants are as prone to forget the absence of a carry, as they are to forget its presence.

Since these initial studies, most experiments have used the dual task technique to investigate the role of different WM components in mental arithmetic. Logie and Baddeley (1987) investigated the effects of articulatory suppression and unattended speech on performance on a counting task where participants were asked either to count the number of dots in an array or to count the number of times a square appeared on a screen. The counting task is thought to involve three types of processing: the perception of an item to be counted; access to the appropriate counting sequence in LTM; and short term storage of a running total. Moreover, the authors suggest that mental counting involves sub-vocal articulation of numbers in the counting sequence. The PL seems to be the mechanism involved in both the sub-vocal articulation of numbers and storage of a running total. The authors found a disruption of counting performance by concurrent articulatory suppression, albeit a subtle effect as the errors tended to be numerically close to the correct answer. The effect of unattended speech was small when the unattended speech was phonologically similar to the numbers used in counting, and it was larger when unattended speech consisted of random number sequences. In both cases the effect was much less than that found with suppression. This result and the finding that errors tended to be close to the correct answer do not fit with the articulatory loop hypothesis. The authors therefore suggest that counting involves a representation of the running total being encoded along several dimensions: one reflected by the articulatory loop and the other being a reflection of priming effects in some other system, which could be an input register (Hitch, 1980) or LTM (Baddeley, 1986)

Logie, Gilhooly, & Wynn (1994) used the dual task methodology to study the role of WM in mental addition, and they suggest that the CE component of WM has a major role in performing the calculations required for mental addition and for the production of approximately correct answers. The sub-vocal rehearsal component of WM is helpful for maintaining accuracy in mental arithmetic. This interpretation fits with that of Dehaene and Cohen (1991) who suggest that there are two mechanisms in calculation: one dealing with accuracy, the other with approximation. Logie et al.'s (1994) data fit less with the model developed by McCloskey (1992) who argues that in mental arithmetic, numbers and number facts are represented in an abstract form and therefore the modality of input or output is irrelevant. This incongruence could be due to differences in the experimental procedures used. Logie et al.'s (1994) participants were not only to respond with a total, they also had to keep in mind running totals to which they added the subsequently presented item. Such a procedure is likely to place greater demands on WM than individual sums (commonly used in this kind of study). Nonetheless, Ashcraft, Donley, Halas, and Vakali (1992) argued that WM resources are required even for relatively simple arithmetic, access to arithmetic facts and their manipulation. Logie et al. (1994) fail to explain adequately why they did not find an interaction between the difficulty of the calculation measured by the number of carries required, and the presence of a secondary task. If the assumption is that the secondary task overloads a common processing resource, being used by the concurrent primary task, then the interference of a secondary task should be greater when the primary task is more difficult. The authors suggest that the system required to keep track of carries may be different from the one maintaining accuracy in calculation. This explanation is tentative while little remains known about how carries are handled by the cognitive system.

So far the only study attempting to explain the process of carrying is by Furst and Hitch (2000). They investigated the role played by executive and phonological components of WM, again using a dual task. They showed that articulatory suppression (involving the PL) impaired the ability to add briefly presented pairs of three-digit numbers. When the numbers were visible for the time required by the participant to solve the operation (and therefore there was no need for temporary storage), articulatory suppression had no effect on performance. Overloading the executive processes with a concurrent Trails task impaired the ability to add numbers even if they were permanently visible. Moreover, performance on the Trails task deteriorated with the increase of the carryings in the addition. The authors concluded that the carrying component of mental arithmetic requires the intervention of executive processes, whereas retaining problem information relies on the PL.

Lemaire, Abdi, and Fayol (1996) investigated whether simple arithmetic requires WM resources with a simple verification task and a secondary task. In the verification task, participants were presented with simple equations such as 8 + 4 = 12 and had to decide if it was "true" or "false" by pressing the appropriate key. The difficulty of the problems (easy vs. hard) and the potential associative confusion (i.e. when the given answer to a problem would be the correct answer for another operation e.g. 8 X 4 = 12; 8 + 4 = 32 (Winkelman & Schmidt, 1974; Campbell & Graham, 1985; Lemaire, Abdi, & Fayol, 1991; Lemaire & Siegler, 1995)) were varied. The secondary tasks were either overloading the PL (with articulatory suppression) and/or the CE (with random letter generation). The predictions were that: the impact of the secondary task should be greater for difficult problems; and the associative confusion effect should be larger when the WM is overloaded. The authors found a greater disruption in performance on "true" problems when both the PL and the CE were overloaded, and a greater disruption in performance on "false" problems when the CE was overloaded. The effect of the concurrent task was greater on difficult problems. The finding of an effect of phonological overload on true problems suggests that the phonological pathway is a privileged route to the true solution representations in memory, and this is perhaps because we learn true arithmetic facts by means of oral repetition. These results together are consistent with the WM resource hypothesis and a role for the CE in simple arithmetic.

De Rammelaere, Stuyven and Vandierendonck (1999), replicated this study with some modifications. A different task was used to tax the CE - the random time interval generation (RIG) (Vandierendonck, De Vooght, & Van der Goten, 1998). In the RIG task, participants are asked to tap a randomly spaced sequence of time intervals on a key to produce an unpredictable, random, rhythm. The requirement to be random and to avoid automaticity taxes the CE. The RIG has the advantage of not taxing other sub-systems of WM, as with the random letter generation used by Lemaire et al. (1996) which involved the PL as well. The problems were restricted to addition. The authors found that random letter generation and RIG interfered with the verification of both true and false problems, replicating Lemaire et al. (1996) in reporting the crucial contribution of the CE in the latencies of all kinds of sums. De Rammelaere et al.'s (1999) results strengthen those findings (Lemaire, Abdi, & Fayol, 1996) as the secondary task used specifically taxed the CE without the involvement of any other subsystem, and they also used additional false answers. As far as the involvement of the PL is concerned their results differed from Lemaire et al.'s (1996) in that they show that the PL is not involved in solving either true or false sums. They suggest two possible explanations for the different finding with true sums. One possibility is that they only used sums with a carry of 1, and as a consequence many possible one digit sums were not studied. They suggest that the PL might play a different role for these sums. The second possibility is that in Lemaire et al.'s (1996) study the secondary task used to overload the PL (i.e. articulatory suppression) might have interfered with the CE, since the instructions given to participants were to say "the" at the rate of exactly one every two seconds. This argument is supported by evidence that strict instructions for the secondary task require an involvement of CE resources (Stuyven, Van der Goten, Vandierendonck, Claeys, & Crevits, 2000). This result is very important for the debate about whether basic arithmetic facts are stored in a language-dependent verbal form (e.g. (Dehaene, 1992; McCloskey, 1992; Dehaene & Cohen, 1995; Noel, Fias, & Brysbaert, 1997; Brysbaert, Fias, & Noël, 1998; Campbell, 1998; Noel, Robert, & Brysbaert, 1998)). For example, the triple-code model of Dehaene (1992; Dehaene & Cohen, 1995) assumes that arithmetic facts are stored in a verbal code, implying that to retrieve a solution, the problem has to be coded in verbal form. This model predicts that articulatory suppression, impairing verbal coding, will interfere with true problems, but not with false ones, since only true problems are stored.

The implications of the contradictory results were explred by De Rammelaere, Stuyven and Vandierendonck (2001) using articulatory suppression, and therefore explaining the role of the PL, on the verification of sums. The results replicated the finding that the PL is not involved in the verification of true or false arithmetical problems whereas the CE is a crucial system for this kind of task (De Rammelaere et al., 1999). These results contradict with models that assume that arithmetic facts are stored in a language-dependent verbal form (Dehaene, 1992; Dehaene & Cohen, 1995). The prediction of Deheane's triple code model is that articulatory suppression, interfering with verbal coding, would also interfere with true problems but not with false ones. The evidence from the set of studies is equivocal on this point (Lemaire et al., 1996; De Rammelaere, Stuyven, & Vandierendonck, 1999; 2001). Other studies have suggested that the assumption of language-dependent verbal coding of arithmetic facts might be incorrect. Pesenti, Thioux, Seron, and De Volder (2000), for instance, found that during an arithmetic fact retrieval task, none of the cortical areas usually involved in verbal processing were activated. Studies of children with poor mathematical abilities also showed that the functioning of the PL is not impaired in these children (Bull & Johnston, 1997; Bull, Johnston, & Roy, 1999; McLean & Hitch, 1999). The independence of the PL and arithmetical abilities is also suggested in the literature from neurological patients. Butterworth, Cipolotti and Warrington (1996) studied a patient with a memory span of three digits but normal abilities in calculation tests, while Semenza, Miceli and Girelli's (1997) patient had a very high digit span but a specific deficit in arithmetical procedures.

On the other hand, support for the triple-code model comes from the findings of Lee and Kang (2002). They examined the relationship between simple arithmetic and WM using either phonological or visuo-spatial suppression. The results show that multiplication places demands on the PL, and subtraction on the visuo-spatial sketchpad. This is not compatible with an amodal vision of number representation (McCloskey, 1992) but fits well with the idea of number representation specific to input/output modality (i.e. triple-code model; (Dehaene, 1992; Dehaene & Cohen, 1995)) and arithmetic types (i.e. modular processing model (Campbell & Clark, 1992; Campbell, 1994; 1997)).

Seitz and Schumann (2000) investigated the role of WM in mental multiplication. The participant had to solve multiplication sums of varying difficulty. Different secondary tasks were used in order to investigate the role of the different sub-components of WM. The authors suggest that solving complex multiplication sums involves PL and CE processes, whereas the retrieval of numerical facts to solve simple multiplication sums involves only the CE. The implication is that access to permanently stored numerical knowledge is controlled via the CE, and that the PL resources are used in complex multiplication for storing partial results.

Noël, Desert, Aubrun and Seron (2001) manipulated the phonological and visual similarity of two numbers to be added, to examine the involvement of the WM components in complex mental addition. They found that phonological similarity had a disruptive effect on both speed and accuracy, whereas visual similarity had no effect. The authors therefore suggest that the PL is the component involved in the temporary storage of addends. These findings are not compatible with the triple-code model of Dehaene (1992; Dehaene & Cohen, 1995), according to which multi-digit calculations are supposed to involve the manipulation of a mental spatial image of the operation. The PL would be used only for the retrieval of the simple arithmetical facts required to solve the intermediate steps of the calculation.

The study of mathematical errors and their relationship with WM has been mostly conducted in the domain of mental arithmetic but this relationship has also been found in other areas such as arithmetical word problems (Fayol, Abdi, & Gombert, 1987) and geometry (Ayres & Sweller, 1990; 1993). These studies suggest that WM load can be a source of errors in several mathematical domains, not only causing the loss of temporary information, but also interfering with the recall and manipulation of information from LTM (Ayres & Sweller, 1990; 1993). Moreover, it has been suggested that on more complex geometry (Ayres & Sweller, 1990) and calculation (Campbell & Charness, 1990) tasks, distinct error clusters emerge at points where the load is heaviest. In a more recent study Ayres (2001) tested the prediction that more errors will occur at points in a problem where the most storage and/or processing of information is required. He used algebraic problems requiring bracket expansion, suggesting that the nature of algebraic bracket tasks leads to an uneven distribution of cognitive load during computation. He found that error clusters increase with cognitive load. From this perspective it is useful to consider the differentiation suggested by Campbell and Charness (1990) between working-memory errors (defined as incorrect substitutions, deletions, and omissions) and calculation errors (defined as fact-retrieval errors).

Semenza et al. (1997) described a patient, M.M., with hydrocephalus and damage to the right dorso-frontal cortex and right upper parietal lobe, with a specific deficit for arithmetical procedures. Unlike previously described cases (Temple, 1991; Girelli & Delazer, 1996), this patient's problems were not attributable to the use of disturbed algorithms but rather to a failure in monitoring the sequence of operations required for the computation. M.M. produced errors in complex written calculation that were not due to a lack of knowledge of the procedures but were likely due to a problem in the monitoring of the ongoing procedure. This case seemed to fit the distinction suggested by Luria (1966) between the performance of frontal patients, who do not show specific difficulty with arithmetical operations but who fail to perform the correct computational programme (because of their difficulty to switch from one operation to another) and parieto-occipital patients, who can show specific difficulties with arithmetic operations. In fact, M.M. did not have difficulty with the computation itself, but with its execution. The hypothesis of a monitoring deficit was supported by the selective difficulty in multiplication problems shown by M.M,. as multiplication requires more long-term control than addition and subtraction, as it requires more intermediate steps. The authors argue that M.M.'s case suggests a specific involvement of monitoring and control processes in the procedural component of the calculation system. The authors went on to define a tentative set of criteria to distinguish different causes of failure in arithmetical procedures and, more specifically, between deficits in the knowledge/memory of the procedures and deficits in monitoring the procedures. According to the authors, a deficit in knowledge of or memory for the procedures would be characterised by: (1) consistent and systematic errors (also called bugs) due to the use of a faulty strategy; (2) no decrease in performance with the proceeding of the operation; (3) no difficulty in knowing when an operation or its subset is completed; (4)

modification with training; and (5) awareness about the specific difficulty. A "monitoring" deficit would manifest as: (1) inconsistent and unsystematic errors, reflecting no consistent strategies; (2) a worsening of performance with the proceeding of the operation; (3) difficulties with ending operations; (4) ineffectiveness of training; and (5) unawareness of the performance. It is possible, although not interpreted by the authors as such, that the described deficit of monitoring and control processes in the procedural component of the calculation system is related to an inefficient functioning of the CE.

Another research approach to WM and calculation, focused on WM abilities (Geary, 1990; Gathercole & Pickering, 2000) and mathematical disabilities in children (Geary, 1993). WM skills are closely linked to children's academic progress during the early years of school (Gathercole & Pickering, 2000) and, particularly, poor WM resources could influence skill development in mathematics and might therefore be a contributing factor to procedural and memory-retrieval deficits (Geary, 1990).

A general criticism of this kind of study is that they usually compare children with arithmetic difficulties to normal achievers of the same chronological age. To overcome this problem, McLean and Hitch (1999) assessed 9-year-old children with difficulties specific to arithmetic comparing them with both age-matched and ability-matched controls. The authors used a task called *Missing Item task,* a paper-and-pencil task with items consisting of one addition and a second, incomplete addition (e.g., $2 + 3 = 4 + ? = ?$). The child was asked to complete the equivalence and then the total. In this task the child has to access LTM to complete the first relationship ($2 + 3 = ?$) and then maintain this information and access LTM again to complete the second relationship ($5 = 4 + ?$)

(McLean & Hitch, 1999). The authors found that, compared to age-matched controls, children with poor arithmetic had a normal phonological WM and were impaired on spatial WM and some executive processes. Compared to ability-matched controls, they were impaired only in holding and manipulating information in LTM. Therefore the authors suggest that executive and spatial aspects of WM are important factors in poor arithmetical achievement.

Until now researchers have attempted to reconcile data about the role of the different components of WM in calculation with the existing models of the calculation system. Despite the great number of studies addressing the role of WM in calculation, a model explaining step by step the processes involved in the various stages of mental calculation is still missing.

1.6. Aims of Thesis

Morris and Jones (1990) suggested that the central executive is able to re-use its resources very rapidly to coordinate complex cognitive processes. This characteristic makes it difficult to study the central executive in isolation from the other subsystems. One way to do so, may be to use demanding dynamic memory tasks, which interfere with what Broadbent (1977) called the "locus of control". A further avenue is to study memory processing in populations with neurological damage where strategic aspects of this processing are impaired, such as patients with damage at the prefrontal cortex (Fuster, 1980; Shallice, 1982).

The aim of this thesis is to investigate WM by examining performance on an updating task devised to pose varying demands on maintenance and inhibition. The task, adapted from Palladino et al. (2001), requires participants to recall information that is "relevant" according to a given criterion, while at the same time inhibiting information that is not relevant to that criterion. Maintenance was measured as the amount of information to be recalled (after being held and manipulated in WM), and conceptualised as the processing capacity of WM[1]. This concept is similar to what would be called "channel capacity" in Broadbent's (1958) conceptualisation, and the "capacity of the focus of attention" in Cowan's (1995) conceptualisation. Inhibition was measured as the amount of information to be suppressed according to a given criterion, and conceptualised as part of the control processes of the Central Executive (i.e. the amount of manipulation carried out by the system). This would correspond to the selective filter impeding the processing of irrelevant information in Broadbent's (1958) conceptualisation, and the control of the direction of the attentional focus in Cowan's (1995) conceptualisation.

1.6.1. Control and maintenance processes in Working Memory

Performance on this task was investigated in healthy participants, to understand the impact of different loads on maintenance and control processes and of different stimulus modalities on recall performance and on error production.

The predictions are:

a) Recall performance on the updating task will be affected by both load on maintenance (more items to recall) and load on control processes (more items to inhibit);

b) Error production due to the recall of "to-be-inhibited" information will only be affected by load on control processes;

[1] The concept of "processing capacity of working memory", and not Baddeley's concept of "processing capacity of Central Executive", is here used because the involvement of the PL in the amount of information recalled cannot be partialled out

c) Recall of numbers will be proven worse than recall of words because of their higher semantic and syntactic complexity.

This will be presented in chapter 2.

1.6.2. Conditions affecting Working Memory

The hypothesis that the central executive component of WM is differentially affected by normal aging, dementia of the Alzheimer's type and brain damage affecting the prefrontal lobes is also investigated by using the updating task in groups with these characteristics. The predictions tested in Chapter 3 are that in normal ageing, maintenance is reduced but control processes are spared. In senile dementia both processes are impaired but in the presence of prefrontal damage only control processes are affected, as suggested by Baddeley (1986). This will be presented in Chapters 4 and 5 respectively.

More specifically, with the updating task used it was expected:

a) A decrease in recall performance (maintenance) with ageing, but no decrease in the ability to inhibit irrelevant information and therefore no increase in the production of errors due to the recall of an item "to be inhibited" (control);
b) Poorer performance on both recall (maintenance) and inhibition of irrelevant information (control) in people with DAT compared to their age-matched controls;
c) Poorer ability to inhibit irrelevant information (control) but no difference in recall performance (maintenance) in people with lesions of the prefrontal lobe compared to healthy controls and people with posterior brain damage.

Other predictions were that:

d) Recall performance is more affected by taxing maintenance processes in elderly people and in people with DAT (but not in people with frontal lesions) compared to their controls;
e) Performance on both recall and inhibition will be more affected by taxing control processes in people with DAT and frontal lesions (but not in elderly people) compared with their controls;
f) Differences are expected in the backwards digit span, where demands on maintenance are coupled with demand on control processes, with a lower performance of participants with DAT and frontal lobe damage, compared to their controls.

1.6.3. Working Memory and calculation

Since the multi-component model of WM was originally conceived as the basis for complex cognitive abilities such as mental arithmetic, this was investigated in groups of participants reported in the literature as having problems in this function as well as in WM.

In order to investigate the relationship between WM and mental arithmetic, performance on the updating task and performance on measures of numerical and calculation processing were measured in two groups of participants with neurological damage - Alzheimer's type dementia and frontal lobe damage (Chapter 4 and 5 respectively). It was expected that:

a) Participants with DAT will perform poorly in the transcoding tasks compared to their controls, as reported in the literature (Tegner & Nyback, 1990; Noel & Seron, 1993; Cipolotti, 1995; Noel & Seron, 1995; Kessler & Kalbe, 1996; Thioux, Seron, Turconi, & Ivanoiu, 1999);

b) Both participants with DAT and prefrontal damage will perform poorly in complex mental calculation compared to their controls, because of their hypothesised difficulties in control processes;
c) No difference will be found between groups in performance on arithmetical facts.

CHAPTER 2: CONTROL AND MAINTENANCE PROCESSES IN WORKING MEMORY: A STUDY OF HEALTHY PARTICIPANTS

2.1. Introduction

The aim of this study was to investigate how the WM system functions in healthy participants investigating span tasks with various materials and an updating task posing increasing demands on memory and inhibition processes.

2.1.1. Maintenance and Control in Working Memory: The Updating task

As discussed in the previous chapter, recent studies investigating the role of WM in complex cognitive functions have focused on the ability to update relevant information and to inhibit irrelevant information. In the previous chapter, the task devised to investigate these two processes devised by Palladino et al. (2001) was described, which required similar effort to complete as reading comprehension. The task described in this chapter is similar to that used by Palladino and colleagues (1998; 2001).

As the central tenet of this thesis is the role of WM in complex cognitive functions such as mental calculation, numbers were used as well as words, so that the task would involve similar material to that held in memory when performing the complex cognitive task (e.g. complex mental calculation). A similar task has been used by De Beni and Palladino (2004) in a study of the effects of ageing, but the authors collapsed data across type of material.

Palladino et al. (2001) described updating as a process of gradual regulation of the activation level of representations. Essential for this process is the creation of a new representation and the suppression of an old representation.

The present study investigated these aspects by studying the correct recall performance and errors produced in an updating task. It is hypothesised that the rate of correct recall will predict the level of functioning of the updating process, whereas investigating the presence of intrusion errors will predict the functioning of the suppression mechanism. In the present study various categories of errors were investigated: same list intrusion errors; previous list intrusion errors; inventions; and omissions. Same list intrusion errors were thought to be due to either a failure in inhibiting incoming irrelevant information or to the intrusion of information from the same list not adequately suppressed. Previous list intrusion errors were thought to be due to the intrusion of old information from LTM which has not been suppressed. Invention errors are thought to represent a failure to control information spontaneously activated in semantic memory.

2.1.2. The use of different stimuli

An initial study compared performance in a simple span test using stimuli of different lengths and categories (e.g. words and numbers, and two and three to five syllables words and number-words) in order to find out the impact of these variables on recall performance. This is necessary since two-digit numbers are used in the WM task and are longer (i.e. formed by a larger number of syllables and longer to read) than the words used in a noun version of the WM task. Differences are also expected in the recall performance with different items (i.e. numbers, nouns and proper names) due to the syntactic and semantic characteristics of these items.

The numbers in fact are very different from the nouns used in this study, which were selected for high imageability and either represented objects or animals. A number is far more abstract than an object or an animal: if one thinks about a chair, for example, certain characteristics of size, shape, texture and colour will come to mind. If one thinks about number six, however, no colour, shape or size will come automatically to mind. Proper names, on the other hand, are not considered to have a meaning -or a "sense" as such, but they have reference [2] (Russell, 1905; Frege, 1960). Furthermore, there is a difference between the semantics of single-digit numbers and two-digit numbers: the semantics of single-digit numbers is, in a way, quite straightforward ("three" means three), whereas the semantics of two-digit numbers is compositional (to understand "twenty-three" one needs to combine the meaning of twenty with the meaning of three). None of the words used in the study are compound words (due to the scarcity of compound nouns and proper names in the Italian language) and this has implications for the semantics of the numbers and words used in the study. Moreover, it is arguable that numbers are semantically more similar one another than nouns, for example 37 is more similar to 53 than a dog to a crocodile. Greater similarity may also lead to greater confusability, however. Considering proper names as having reference but no sense, it is difficult to tell whether Elisabetta is more or less similar to Francesco than the numbers 46 to 59.

The syntax of numbers, and in particular complex numerals, is quite different from that of other words. Whereas the syntax of single digit numbers is relatively simple, it has been suggested by Hurford (1975; 1987) that most complex numerals are constructed through multiplication (e.g. five hundred = 5 x 100) and addition (e.g. thirty seven = 30 + 7). The words used in the study (both

[2] "The sense of a proper name is grasped by everybody who is sufficiently familiar with the language or totality of designations to which it belongs, but this serves to illuminate only a single aspects of the reference, supposing it to have one. Comprehensive knowledge of the reference would require us to be able to say immediately whether any given sense belongs to it. To such knowledge we never attain" (1977)

nouns and proper names), instead, were non compositional and their syntax is therefore simpler.

2.1.3. Errors

Special attention will be given to the errors produced during the updating task, particularly intrusion errors. During the updating task the participant is required to process each incoming item and attribute the correct activation to it, updating this activation as the task goes along. If an item is wrongly activated or if the activation is not updated, this might interfere with the retrieval of relevant information and lead to errors. A failure in the suppression mechanism will widen the number of possible candidates and therefore increase the possibility of making an intrusion error (Palladino et al., 2001). It is proposed that the presence of intrusion errors can inform about the functioning of the suppression mechanism, whereas the rate of correct recall is indicative of the level of functioning of the updating process.

2.1.4. Hypotheses

Firstly the possibility that the length or category of the items would impact recall in a span test was investigated, using similar materials as in the updating task to understand the role of these two factors in a more complex task. As previously discussed, since two-digit numbers are both semantically and syntactically more complex than nouns and proper names of the same length, performance on the two-digit span test was expected to be worse than performance on the span tasks with nouns and proper names of the same length. A word-length effect was also predicted, in accordance with the idea that a greater number of short words can be recalled compared to long words (Baddeley et al., 1975). This effect was expected to be larger for numbers, as the differences between one digit-numbers and two-digit numbers in syntactic and semantic complexity is much greater than the differences between nouns or proper names two and three to five syllables long.

Secondly, different processes that might be involved in an updating task, particularly maintenance (involved in the updating of relevant information) and control (involved in the inhibition of irrelevant information) were investigated. These two processes are likely to involve specific components of WM, and in particular the CE (Morris & Jones, 1990). Some authors have argued that success in remembering relevant information and suppressing irrelevant information in WM is related to the availability of resources in the WM system (Engle, Cantor, & Carullo, 1992; Conway, Tuholski, Shisler, & Engle, 1999). The present study investigated this by using an updating task which differentially taxes maintenance and control processes, aimed at distinguishing between load on control processes (i.e. the number of items to be inhibited, thought to be posing demands on the control processes of CE) and load on maintenance (i.e. the number of items to be recalled, thought to be posing demands on the PL and on the capacity of the of CE system, i.e. on the WM storage capacity (Cowan, 2004; 2005)). The effect of these two conditions and their interaction on the recall performance and error production will be investigated.

The predictions are that recall performance on the updating task will be affected by both load on maintenance (more items to recall) and load on control processes (more items to inhibit). The production of intrusion errors will only be affected by the load on control processes. Load on maintenance and load on control were expected to interact because of the limited processing capacity of the CE (or WM storage capacity, in Cowan's (2004; 2005) conceptualisation): with a small load on maintenance processes it is expected that the load on control processes would have a smaller effect on recall and that no significant difference will be found in recall performance between conditions of control. Moreover it was expected that performance recalling words would be better than performance recalling numbers because of the greater semantic and syntactic complexity of two digit numbers compared to the words used in the study.

2.2. Method

2.2.1. Participants

Twenty two healthy adults took part in this study (10 males and 12 females), aged from 34 to 55 (mean 45.9 years, standard deviation = 6.12 years) with between 8-17 years of education (mean 12.7 years, standard deviation = 4.43 years).

2.2.2. Experimental Task

2.2.2.1. Span tests

Span tests with several stimuli were administered, using various stimuli to measure STM capacity of the participants, in tests relying mostly on the phonological loop component. The stimuli selected matched those used in the updating task, and allowed the manipulation of word length or lexico-semantic category.

Table 2.1 shows the six different sub-categories investigated, detailing the lexico-semantic category and the length of the items in syllables. Proper names were used in order to have a condition with a reference but no meaning (Frege, 1960) as used by Campbell and Butterworth (1985).

Table 2. 1:Span tests – Items' categories and length in syllables

Item	Nouns	Proper names	Numbers
2 syllables	2-syllable nouns	2-syllable proper names	1-digit numbers
3 to 5 syllables	3/5-syllable nouns	3/5-syllable proper names	2-digit numbers

The stimuli for the one-digit span (forward and backwards) were the same as those used in the digit span subtest of the WAIS-III (Wechsler, 1997). The two-digit numbers used were chosen from the range of two-digit numbers, excluding teens and multiples of ten (in order to make the stimuli homogeneous). The lists were composed so to avoid effects of phonological similarity. Therefore, where possible, numbers with the same digit in the same position were not used in the same list (e.g. 37 and 57, or 64 and 69). Moreover, where possible, the numbers for the span task were different from those used in the updating task during the same testing session.

The nouns were highly familiar and imageable items selected from Burani, Barca and Arduino's database (2001). These stimuli were different from those used in the updating task (see below), in order to avoid priming effects between the two tasks. The proper nouns were selected from among the most common in a list of over 1600 Italian names (http://www.nomix.it, 2003).

During all span tasks, the participants were presented with lists of increasing length (from two to eight items). There were two lists for each length. If participants were able to recall all the items on the list in the correct order, they were presented with a longer list. If they did not recall the list correctly, they were presented with the second list of the same length. If then they were able to recall all the items in the second list in the correct serial order, a list with one more item was presented. If the participant was still unable to correctly recall the second list of that length, the test finished and the participant's span was calculated as the length of the last list he recalled correctly.

The instructions to the participant were to repeat a series of items read by the experimenter in the same order of presentation for all span tests except for the digit span backwards. Here, the instructions were to recall the items presented by the experimenter backwards, i.e. starting with the last item presented and finishing with the first one (e.g. for 7-1-9, the participant will have to say 9-1-7). All numbers/words in all conditions were read to the participant by the experimenter at the rate of one word per second. The test begins with an example trial. The span was calculated as the highest number of items recalled in the correct serial order. The complete set of span tests used in this thesis is reported in Appendix I.

2.2.2.2. Updating Task

A task of WM was devised to test the ability of the participants to update relevant and inhibit irrelevant information during a task of free recall with a semantic criterion. It was adapted from Palladino et al. (2001).

Sixteen lists of words (eight lists of names of animals and eight lists of names of objects) and sixteen lists of 2-digit numbers (odd in half of the lists even in the other half) were presented to the participants. The test was split across two experimental sessions (eight lists of words and eight of numbers per session).

The words were bi- or tri-syllabic highly familiar and imageable nouns selected from the same database as the nouns used in the span tests (Burani, Barca, & Arduino, 2001). The words referred to nouns of animals or objects of different size. The nouns used in the study were selected via a pilot study in which 23 participants were asked to judge, on a scale from 1 (very small) to 9 (very big), the dimensions of 53 animals and 100 objects (the order of presentation was randomised). Only the items with a clearly discriminable size were used. A second pilot study (with 20 participants) was conducted, in order to check the discriminability of the selected items within the lists. The lists were balanced for number of syllables.

Two-digit numbers between 22 and 99 were associated to the animals and objects according to the size-judgement from the pilot study, and used to compose the lists with numbers. In this way the lists were similarly constructed in that each number corresponded to an object or animal. The numbers excluded were teens, and multiples of ten and numbers containing 1 as a unit: since numbers with "1" as decade (10-19) were removed, numbers with "1" as the unit (e.g. 21, 31, ..., 91) were also removed so that each digit (2-9) would have an equal rate of occurrence. Moreover, in this way there was an equal number of odd and even numbers. A possible source of confusion is that the number of syllables composing the number-words is bigger (3 to 5 syllables), but the use of two-digit numbers was necessary in order to have a large number of different items, and also because they are more likely to occur in complex mental calculation. Other limitations related to the use of two digit numbers concern the different syntactic and semantic complexity of these numbers compared to the words used in the study, as discussed above. These limitations need to be taken into account when interpreting the results of the studies.

The stimuli were verbally presented by the experimenter at the rate of one item per second and the participants were required to recall a predefined number of the smallest items presented. This therefore required the participant to constantly update the incoming information and to inhibit or suppress the irrelevant items.

The thirty-two lists were graded in length and task difficulty. The task difficulty was determined by the number of items to recall and to inhibit (i.e. items in the list that did not fulfil the semantic criterion, but might have fulfilled it temporarily before all items of the list had been presented).

There were four recall conditions, with the participant having to recall one (R1), two (R2), three (R3) or four (R4) of the smallest items presented, and two inhibition conditions, with the participant having to ignore (or initially recall and then inhibit) one (condition of Low Inhibition, LI) or three items (condition of High Inhibition , HI).

The lists' length varied between two and seven items. Table 2.2 shows the length of the lists of the updating task, detailing the amount of recall and inhibition required. For every cell in Table 2 there are four lists: two for words (animals/objects) and two for numbers (odd/even).

Table 2. 2:Updating task - Length of the lists and types

Recall (number of items to recall)	Inhibition	
	Low (LI) (1 item to inhibit)	High (HI) (3 items to inhibit)
1	2 items	4 items
2	3 items	5 items
3	4 items	6 items
4	5 items	7 items

An example of list with words, where to remember two and inhibit three items is: "GRANCHIO – LUPO – CERVO – VIPERA - CANGURO" (i.e.: crab – wolf – deer – viper - kangaroo). Here, the participant must remember the two smallest animals in the list (i.e. crab and viper). An example of list with numbers, where to remember four items and inhibit one is: "28 – 82 – 54 – 46 – 34". Here the items to recall are 28, 54, 46 and 34 (i.e. the four smallest numbers in the list) (for the complete Updating task see Appendix II). In order to perform correctly, the participant, while listening to the presented items, has to constantly update the information with the new item presented and to inhibit one of the previously recalled ones that is no longer fulfilling the criterion.

Instructions were given to the participant before the presentation of each list, specifying the number of items to be recalled and their category (e.g. animals). Three trial lists were presented at the beginning, to ensure the participants understood the task. The stimuli were pre-recorded and presented to the participant through a Sony mini-disc player. The participant gave a verbal response at the end of each list.

In the updating task the percentage of correct items recalled was considered as a measure of Recall. The errors were divided into: intrusion errors from the same list (recall of words actually presented to the participant in that list but not fulfilling the semantic criterion); intrusion errors from a previous list (recall of words actually presented to the participant but in a previous list); inventions (recall of words never presented to the participant); and omissions (the participant did not recall the word).

The main difference to previous updating tasks used by Paladino, De Beni and colleagues (1998; 2001; 2004) is that, in order to investigate performance under different amounts of load on maintenance and control processes, lists were of different lengths. This was achieved by excluding "filler" items used in previous studies. Another difference was that the same-list-intrusion-errors were analysed together. This was necessary because of the relatively small amount of this kind of errors, but it had the limitation of not allowing a distinction between intrusions of no-longer-relevant items that had to be initially retained and then suppressed, and intrusions of items to be immediately inhibited for not fulfilling the criterion.

2.3. Results

2.3.1. Span tests

A 3X2 within-subjects Analysis of Variance (ANOVA) was performed in order to compare the recall of items depending on length (bi-syllabic items or three to five-syllable items) and on category (i.e. numbers, objects and animals, and proper names). The within-subjects independent variables were STIMULUS with three levels (NUMBER, when the stimulus to recall was a number; NOUN, when the stimulus to recall was a name of object or animal; PROPER NAME, when the stimulus to recall was a proper name), and LENGTH with two levels (2-SYLL and 3/5-SYLL). The dependent variable was the number of items correctly recalled in the correct order. Bonferroni correction was used when multiple comparisons were performed on the data, and all the significance values reported include this correction where necessary.

Statistically significant main effects were found for STIMULUS [$F(2,33) = 6.06$; $p<0.01$], and for LENGTH [$F(1,21) = 122.60$; $p<0.001$]. This was investigated further by conducting a Paired Samples t-test comparing each of the three levels of the variable with the others. The results show that in conditions with numbers, recall performance is significantly better than performance with nouns [$t(21) = 2.75$; $p<0.05$], and proper names [$t(21) = 2.93$; $p<0.05$][3]. The main effect of LENGTH is due to the performance on the condition with bi-syllabic items being better than in the condition with longer items to recall.

[3] The latter two conditions did not significantly differ from one another [$t(21) = 1.45$; $p>0.05$].

A significant interaction was found for STIMULUS X LENGTH [$F(2,42) = 19.72$; $p<0.001$]. In order to investigate this interaction between, a Paired Samples t-test was performed comparing each type of STIMULUS for each level of LENGTH. As illustrated in Figure 2.1, the results show that in the 2-SYLL condition, the digit span (i.e. 2-SYLL NUMBER) is significantly longer than the word span for two-syllable nouns [$t(21) = 6.24$; $p<0.01$], and from the word span for two-syllable proper names [$t(21) = 4.42$; $p<0.01$]. The difference between span for two-syllable nouns and two-syllable proper names is not significant[4]. In the 3/5-SYLL condition, the only significant difference was found between two-digit numbers (i.e. 3/5-SYLL NUMBER) and three to five-syllable nouns [$t(21) = -2.89$; $p<0.05$], with the span with numbers being smaller than the span with nouns. No difference was found between the other levels of STIMULUS[5].

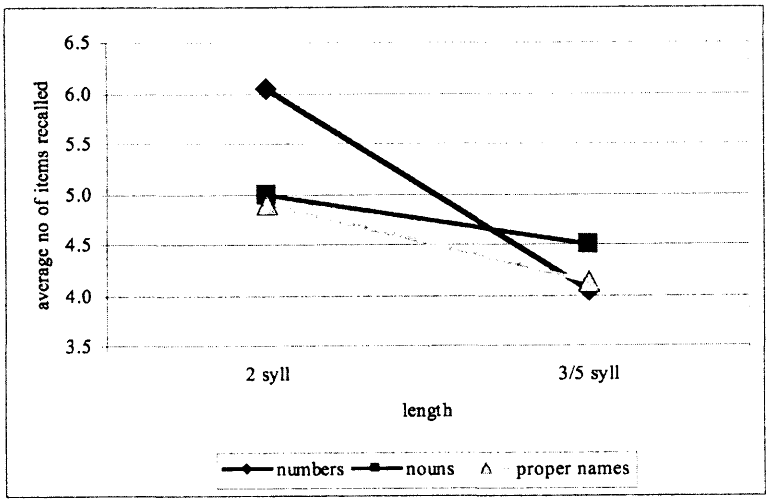

Figure 2. 1: Span tests - interaction STIMULUS X LENGTH

[4] [$t(21) = 0.42$; $p>0.05$]

[5] 3/5-SYLL NUMBER vs. 3/5-SYLL PROPER NAME [$t(21) = -0.49$; $p>0.05$]; 3/5-SYLL NOUN vs. 3/5-SYLL PROPER NAME [$t(21) = 2.01$; $p>0.05$]

2.3.2. Updating task

In the Updating task, separate analyses were conducted in order to investigate recall performance (measured as the percentage of correct items recalled), the production of intrusion errors of items from the same list, the production of intrusion errors of items presented in a previous list, the production of items invented by the participant, and omissions. Errors were measured as the percentage of items incorrectly recalled (or not recalled, in the case of omissions) from the total number of presented items. Bonferroni correction was used when multiple comparisons were performed on the data, and all the significance values reported include this correction where necessary.

2.3.2.1. Correct recall

A 2x4x2 mixed design ANOVA was conducted to analyse differences in recall performance depending on: the type of stimulus to be recalled (i.e. nouns or numbers); the load on maintenance processes (i.e. the number of items participants were asked to recall); and the load on inhibitory processes (i.e. the number of irrelevant items participants must ignore in order to recall the correct items).

The within-subjects factors were: STIMULUS with two levels (NOUN and NUMBER), RECALL with four levels (R1, R2, R3, R4), and INHIBITION with two levels (LI and HI). The dependent variable was the percentage of correctly recalled items.

The analysis reveals a significant main effects of INHIBITION [$F(1,21) = 64.71$, $p<0.001$]. This is characterised by a worse performance on recall when the load on control processes is higher (HI) compared to when the load on control processes is lower (LI).

A main effect of RECALL [$F(2,35) = 73.37$, $p<0.001$] was also found. A polynomial contrast showed that the effect is best accounted for by a quadratic[6] decrease [$F(1,21) = 86.51$; $p<0.001$] across conditions of recall. This is shown in Figure 2.2, where a little difference can be seen between one and two items to recall, but similar and larger differences can be observed between two and three items and between three and four items.

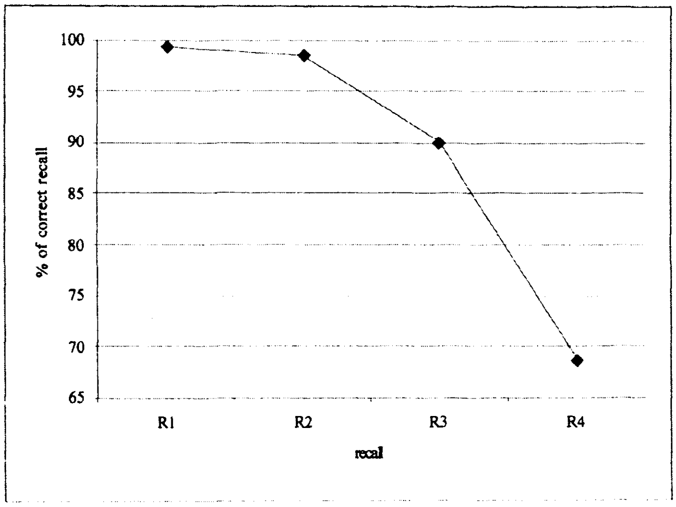

Figure 2. 2: Updating task- Correct Recall - main effect of RECALL

A main effect of STIMULUS [$F(1,21) = 29.45$, $p<0.001$] was also found, due to the performance of recall with numbers being significantly worse than the performance with words.

The interaction INHIBITION X RECALL is significant [$F(1,31) = 5.51$, $p < 0.02$]. A Paired Samples t-test was conducted for each level of RECALL, comparing the performance on the different levels of INHIBITION (LI and HI). As figure 2.3 illustrates, the t-test shows that the difference between LI and HI is

[6] A linear decrease was also found to be significant [$F(1,21) = 91.84$; $p<.0.001$]

only significant when the task required the recall of four items (R4) [t(21)= 3.74, p<0.01], but not at any of the other three levels[7].

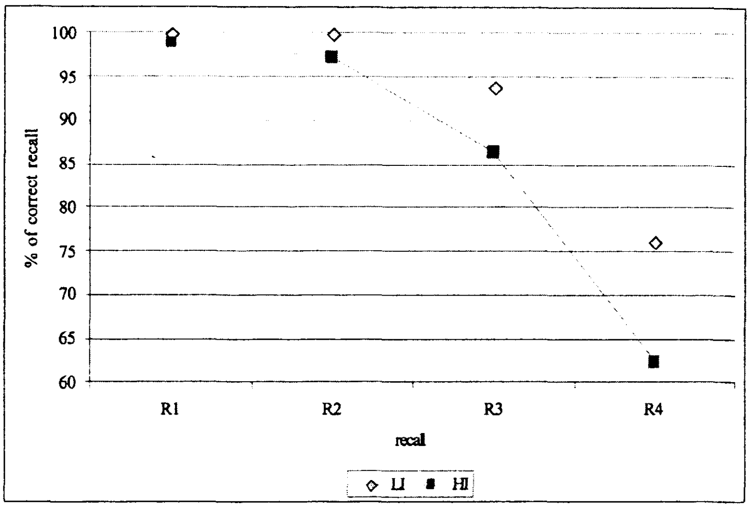

Figure 2. 3: Updating task- Correct Recall - interaction INHIBITION X RECALL

The interaction RECALL X STIMULUS is also significant [F(2,43) = 32.68, p < 0.001][8]. In order to analyse this interaction, a Paired Samples t-test was conducted for each level of RECALL, comparing the performance at the different levels of STIMULUS (i.e. noun and number). Figure 2.4 shows that the difference between the numbers and words is only present when the task requires the recall of four items (R4) [t(21)= 8.26, p<0.005], and not at the other levels[9].

[7] R1 [t(21)= 1.00, p>0.05], R2 [t(21)= 2.02, p>0.05], and R3 [t(21)= 2.62, p>0.05]
[8] The other interactions (INHIBITION X STIMULUS [F (1,21) = 0.54, p>0.05]; INHIBITION X RECALL X STIMULUS [F (2,40) = 0.27, p>0.05]) were not significant.
[9] R1 [t(21)= 1.00, p>0.05], R2 [t(21)= -0.57, p>0.05], and R3 [t(21)= 0.71, p>0.05]

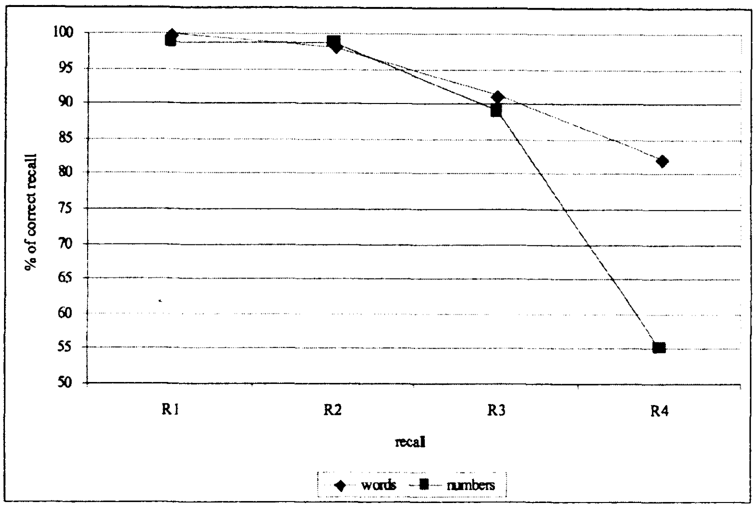

Figure 2. 4: Updating task- Correct Recall - interaction RECALL X STIMULUS

2.3.2.2. Same list intrusion errors

A 2x4x2 mixed design ANOVA was conducted to investigate differences in the production of intrusion errors of items from the same list, depending on: the type of stimulus to be recalled (i.e. nouns or numbers); the load on maintenance processes (i.e. the number of items participants were asked to recall); and the load on inhibitory processes (the number of irrelevant items participants must ignore in order to recall the correct items). The independent variables were the same as in the previous analysis, and the dependent variable was the percentage of intrusions from the same list (as a proportion of the total number of responses).

The analysis revealed a significant main effects of INHIBITION [$F(1,21) = 12.42$, $p<0.005$][10]. This is explained by more intrusions from the same list being produced when the load on control processes is higher (HI) compared to when the load on control processes is lower (LI).

[10] No other main effect was found: RECALL [$F(3,63) = 2.37$, $p>0.05$]; STIMULUS [$F(1,21) = 2.59$, $p>0.05$].

The interaction RECALL X STIMULUS [$F(2,40) = 3.54$, $p<0.05$] is significant[11]. A Paired Samples t-test was conducted for each level of RECALL, comparing the intrusion errors from the same list produced at the different levels of STIMULUS (NOUN and NUMBER). No significant difference between nouns and numbers was found[12]. However, the trend is for same list intrusion errors to be produced more with words than with numbers, but only when the demands to the memory system are higher (i.e. with three or four items to recall).

2.3.2.3. Previous list intrusion errors

A 2x4x2 mixed design ANOVA was conducted to assess differences in the production of intrusions from a previously presented list, depending on: the type of stimulus to be recalled (i.e. nouns or numbers); the load on maintenance processes (i.e. the number of items participants were asked to recall); and the load on inhibitory processes (i.e. the number of irrelevant items participants must ignore in order to recall the correct items).

The independent variables were the same as in the previous analyses, and the dependent variable was the percentage of intrusions from a previous list (as a proportion of the total number of responses).

A main effects of RECALL [$F(1,26) = 26.89$, $p<0.001$] was found. As illustrated in Figure 2.5, a polynomial contrast showed that the factor RECALL is better accounted for by a quadratic[13] increase [$F(1,21) = 18.39$; $p<0.001$]: increasingly more errors are produced when more items have to be recalled,

---

[11] The other interactions were not significant (INHIBITION X RECALL [$F(3,63) = 1.98$, $p>0.05$]INHIBITION X STIMULUS [$F(1,21) = 1.46$, $p>0.05$]; and INHIBITION X RECALL X STIMULUS [$F(3,63) = 1.28$, $p>0.05$]).

[12] R1 [$t(21)= -1.00$, $p>0.05$], R2 [$t(21)= -1.00$, $p>0.05$], and R3 [$t(21)= 2.08$, $p>0.05$], R4 [$t(21)= 8.26$, $p>0.05$]

[13] A linear [$F(1,21) = 34.26$; $p<.0.001$] and a cubic[$F(1,21) = 7.41$; $p<.0.02$] increase were also found to be significant

particularly when the load on maintenance processes is highest (i.e. with four items to recall).

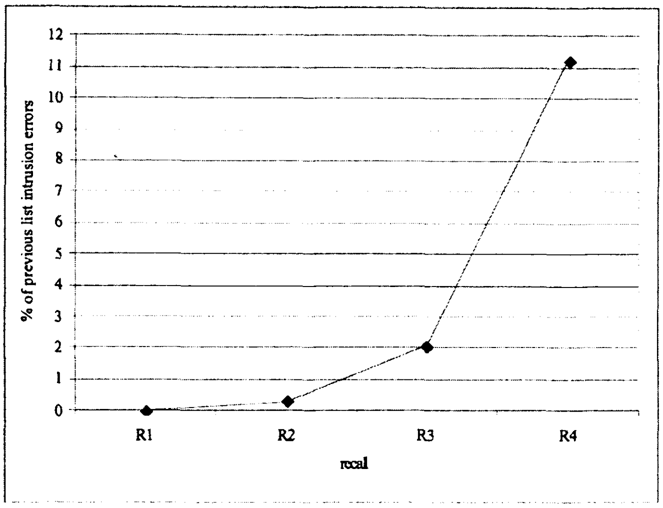

Figure 2. 5: Updating task- Previous List Intrusion Errors - main effect of RECALL

A main effect of STIMULUS [$F(1,21) = 33.81$, $p<0.001$] was also found[14]. This is explained by more intrusion errors from a previous list being produced when recalling numbers compared to when recalling words.

The interaction RECALL X STIMULUS is significant [$F(1,27) = 17.17$, $p<0.001$]. A Paired Samples t-test was conducted for each level of RECALL, comparing the previous list intrusion errors produced at the different levels of STIMULUS (i.e. noun and number). Figure 2.6 shows that no significant difference between nouns and numbers is found in conditions of low load on the memory system (i.e. R1; R2)[15], but it is found to be significant when the items to recall numbered three (R3 [$t(21)= -2.88$, $p<0.05$]) or four (R4 [$t(21)= -4.86$, $p<0.005$]).

[14] No main effect of INHIBITION was found [$F(1,21) = 2.76$, $p>0.05$].

[15] R1 [n.s.: Could not compute the difference since all scores were equivalent], R2 [$t(21)= -1.00$, $p>0.05$]

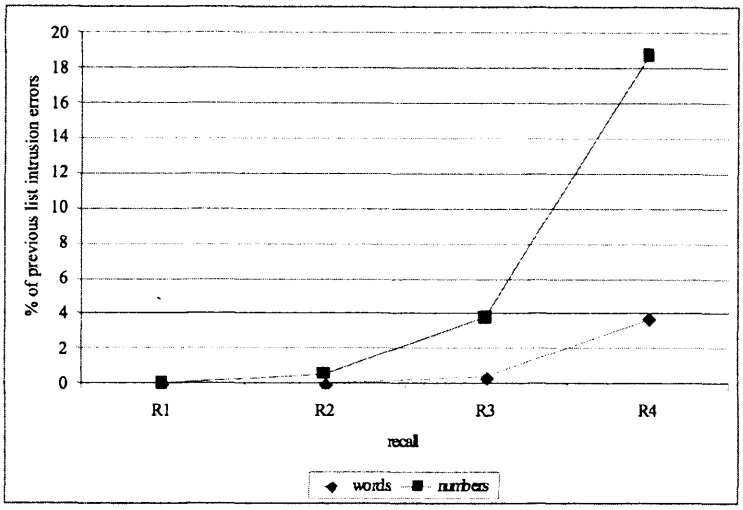

Figure 2. 6: Updating task- Previous List Intrusion Errors - interaction RECALL X STIMULUS

The interaction INHIBITION X RECALL X STIMULUS [F(2,37) = 4.89, p<0.02] is also significant[16]. A Paired Sample t-test compared the two levels of STIMULUS (i.e. noun and number) at each level of RECALL and of INHIBITION. The results show that for words and numbers in conditions of both low and high inhibition there is a difference in the production of intrusion errors when the level of recall is very high (LI: R4 [t(21)= -5.76, p<0.005]; HI: R4[t(21)= -3.13, p<0.05]) but not when it is low[17].

2.3.2.4. Invention errors

A 2x4x2 mixed design ANOVA was conducted to assess variation in the production of false recall (i.e. items that were not present in any of the presented lists), depending on: the type of stimulus to be recalled (i.e. nouns or numbers); the load on maintenance processes (i.e. the number of items participants were

[16] The other interactions (INHIBITION X RECALL [F(2,43) = 1.92, p>0.05], and INHIBITION X STIMULUS [F(1,21) = 0.00, p>0.05];) were not significant.

[17] LI: R1, R2 [n.s.: Could not compute the difference since all scores were equivalent], R3 [t(21)= -1.00, p>0.05]; HI: R1 [n.s.: Could not compute the difference since all scores were equivalent], R2 [t(21)= -1.00, p>0.05], R3 [t(21)= -2.59, p>0.05]

asked to recall); and the load on inhibitory processes (the number of irrelevant items participants must ignore in order to recall the correct items).

The independent variables were the same as in the previous analyses, and the dependent variable was the percentage of invention errors (as a proportion of the total number of responses).

The analyses revealed significant main effects of RECALL [$F(2,48) = 6.99$, $p<0.001$]. A polynomial contrast shows a linear increase [$F(1,21) = 21.48$; $p<0.001$], with increasingly more inventions produced with more items to be recalled, as illustrated in Figure 2.7.

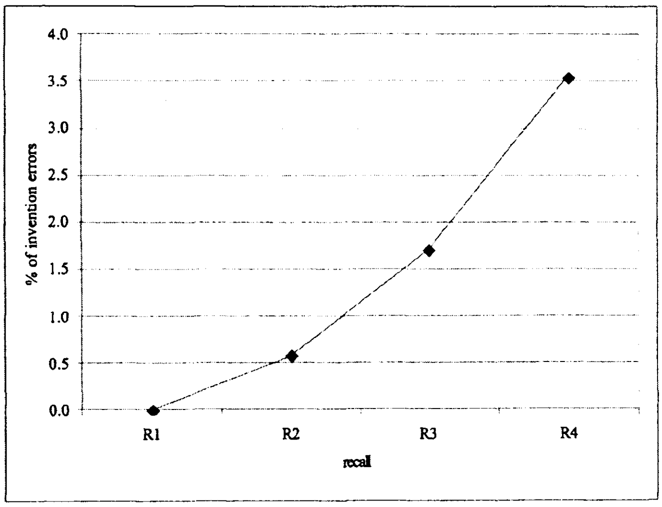

Figure 2. 7: Updating task- Invention Errors -main effect of RECALL

A main effect of STIMULUS is also significant [$F(1,21) = 16.45$, $p<0.002$][18], and it is explained by more invention errors being produced when recalling numbers than when recalling words.

The interaction RECALL X STIMULUS [$F(3,63) = 6.80$, $p<0.001$], is statistically significant[19]. In order to analyse this interaction, a Paired Samples t-

[18] The main effect of INHIBITION was not significant [$F(1,21) = 1.21$, $p>0.05$].

[19] The other interactions (INHIBITION X RECALL [$F(3,63) = 0.76$, $p>0.05$], and INHIBITION X STIMULUS [$F(1,21) = 0.17$, $p>0.05$]; INHIBITION X RECALL X STIMULUS [$F(3,63) = 0.05$, $p>0.05$]) were not statistically significant.

test was conducted for each level of RECALL, comparing the invention errors produced for nouns and numbers. As illustrated in Figure 2.8, the difference between the two levels of stimulus is only significant in the condition of highest load on the memory system (R4 [t(21)= -4.86, p<0.005]). In all other conditions of load on maintenance, no difference in the production of inventions between words and numbers is statistically significant[20].

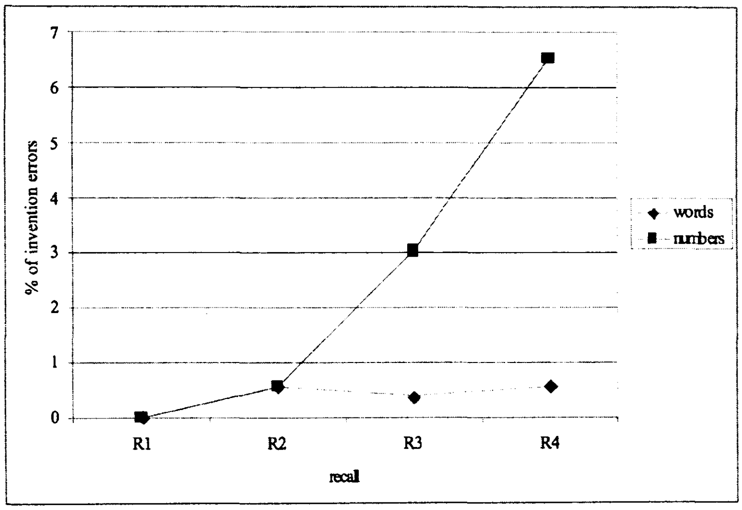

Figure 2. 8: Updating task- Invention Errors -interaction RECALL X STIMULUS

2.3.2.5. Omission errors

A 2x4x2 mixed design ANOVA was conducted to assess variation in the percentage of omissions depending on the type of stimulus to be recalled (i.e. nouns or numbers), on the load on maintenance processes (i.e. the number of items participants were asked to recall), and on the load on inhibitory processes (i.e. the number of irrelevant items participants must ignore in order to recall the correct items).

[20] R1, R2 [n.s.: Could not compute the difference since all scores were equivalent], R3 [t(21)= -1.78, p>0.05]

The independent variables were the same as in the previous analyses, and the dependent variable was the percentage of omissions (as a proportion of the total number of responses).

The main effect of INHIBITION is significant [$F(1,21) = 19.55$, $p<0.001$], and it was explained by a worse performance (i.e. more omissions) when the load on control processes was higher (HI) compared to when the load on control processes was lower (LI).

RECALL is also a significant main effect [$F(3,63) = 22.15$, $p<0.001$][21]. A polynomial contrast shows that the factor RECALL is better accounted for by a quadratic[22] increase [$F(1,21) = 42.93$; $p<0.001$]. In order to further investigate this trend, a Paired Sample t-test was performed comparing each consecutive level of RECALL. As illustrated in Figure 2.9, this shows a significant difference in performance between only the last two levels of RECALL (i.e. three and four items to recall) [$t(21) = -6.55$; $p<0.005$][23].

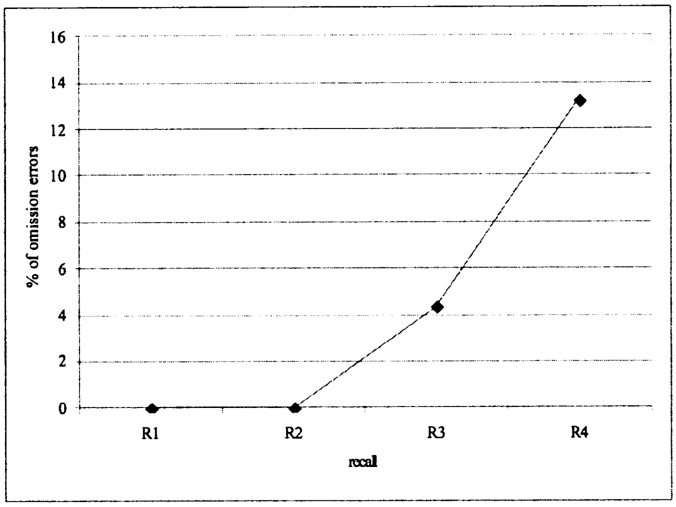

Figure 2. 9: Updating task- Omission Errors -main effect of RECALL

[21] No significant main effect of STIMULUS was found [$F(1,21) = 3.30$, $p>0.05$].
[22] A linear increase was also found to be significant [$F(1,21) = 24.22$; $p<.0.001$].
[23] No significant difference between R1 and R2 [n.s.: Could not compute the difference since all scores were equivalent], nor between R2 and R3 [$t(21) = -2.26$; $p>0.05$].

The interaction INHIBITION X RECALL is significant [$F(3,63) = 4.41$, $p < 0.01$]. To investigate this interaction, a Paired Samples t-test was conducted for each level of RECALL, comparing the percentage of omissions at the different levels of INHIBITION (LI and HI). This shows that the difference between LI and HI is not significant at any level of RECALL[24].

The interaction RECALL X STIMULUS is significant [$F(3,63) = 6.47$, $p<0.002$].[25] A Paired Samples t-test was conducted for each level of RECALL, comparing the performance at the different levels of STIMULUS (NOUN and NUMBER). As illustrated in Figure 2.10, this shows that the difference between the two levels of stimulus is only significant with the highest load on recall (R4) [$t(21)= -3.35$, $p<0.02$], and it is not significant at the other levels[26].

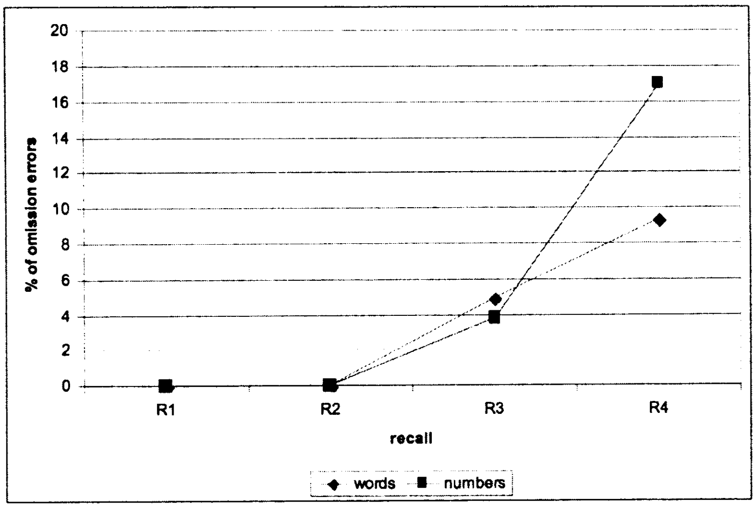

Figure 2. 10: Updating task- Omission Errors -interaction RECALL X STIMULUS

[24] R1, R2 [n.s.: Could not compute the difference since all scores were equivalent]; R3 [$t(21)= -0.53$, $p>0.05$; R4 [$t(21) = -2.64$; $p>0.05$].

[25] The other interactions (INHIBITION X STIMULUS [$F(1,21) = 3.30$, $p>0.05$]; INHIBITION X RECALL X STIMULUS [$F(3,63) = 1.25$, $p>0.05$]) were not significant.

[26] R1, R2 [n.s.: Could not compute the difference since all scores were equivalent]; R3 [$t(21)= -0.53$, $p>0.05$].

2.3.2.6. *Summary of Updating Results*

Table 2.3 illustrates a summary of the results of the Updating task. A significant difference is found on recall performance between conditions of low and high inhibition: significantly more items are correctly recalled in the condition of low inhibition, compared to the condition of high inhibition. However, this is only significant when the demands on recall are highest. The number of items to be recalled also influences recall performance. The recall of nouns is significantly better than the recall of numbers, but this is only the case when the demands on recall are highest.

When error types are analysed, the production of intrusion errors from items of the same list is only influenced by the demands on inhibition, with more intrusions being produced when a larger number of items had to be inhibited. The production of intrusion errors from a previous list is influenced by the amount of items to be recalled. This variable was also affected by the stimulus to be recalled: significantly more errors are made when recalling numbers than when recalling words. However, this is only the case at higher levels of demand on recall (i.e. when 3 or 4 items had to be recalled).

A similar pattern is found for the production of invention errors. The number of items to be recalled influences performance linearly, with proportionally more errors being produced with increased demand on recall. Moreover, a greater number of errors is produced when recalling numbers compared to nouns, but only when four items have to be recalled.

Omission errors are influenced by the load on inhibition: more items are omitted when the load on inhibition is high. They are also influenced by load on recall. Finally, more items are omitted when recalling numbers than when recalling nouns, but only when there are four items to recall.

Table 2. 3: Updating task- Summary of results

		RESULTS
RECALL	INHIBITION	LI>HI
	RECALL	Quadratic decrease
	STIMULUS	W>N
	INHIB X RECALL	LI>HI with R4
	INHIB X STIMULUS	n.s.
	RECALL X STIMULUS	W>N with R4
	INHIB X REC X STIM	n.s.
SAME LIST INTRUSIONS	INHIBITION	LI>HI
	RECALL	n.s.
	STIMULUS	n.s.
	INHIB X RECALL	n.s.
	INHIB X STIMULUS	n.s.
	RECALL X STIMULUS	n.s.
	INHIB X REC X STIM	n.s.
PREVIOUS LIST INTRUSIONS	INHIBITION	n.s.
	RECALL	Quadratic decrease
	STIMULUS	W>N
	INHIB X RECALL	n.s.
	INHIB X STIMULUS	n.s.
	RECALL X STIMULUS	W>N with R3 and R4
	INHIB X REC X STIM	n.s.
INVENTIONS	INHIBITION	n.s.
	RECALL	Linear decrease
	STIMULUS	W>N
	INHIB X RECALL	n.s.
	INHIB X STIMULUS	n.s.
	RECALL X STIMULUS	W>N with R4
	INHIB X REC X STIM	n.s.
OMISSIONS	INHIBITION	LI>HI
	RECALL	Quadratic decrease
	STIMULUS	n.s.
	INHIB X RECALL	n.s.
	INHIB X STIMULUS	n.s.
	RECALL X STIMULUS	W>N with R4
	INHIB X REC X STIM	n.s.

Key: LI=Low Inhibition; HI=High Inhibition; R1, R2, R3, R4=1 item to recall, 2 items to recall etc.; W=Words (i.e. nouns); N=Numbers; > = better performance (i.e. more items recalled or fewer errors); < = worse performance (i.e. fewer items recalled or more errors); Decrease= decrease in performance (i.e. decrease in recall or increase in errors); n.s. = not significant

2.4. Discussion

The aim of this study was to investigate how the STM and the WM system function in healthy participants. In particular the effects of word length and semantic category of the items were investigated in STM span tasks. The effects of the category of the items and load on maintenance and control processes were also investigated in an updating task. In the STM span, numbers, nouns and proper names were used as to be recalled items. The length of the items was also investigated by using conditions where the items were bi-syllabic and conditions where the items were of three to five syllables length. The WM system was investigated by analysing performance on an updating task devised to pose increasing demands on memory and inhibition processes, in order to study the effects of load on maintenance and control processes.

Table 2.4 summarises the main predictions made and results found on the Span tests. Firstly the possibility that the length and/or the category of the items would affect the recalling in a span test was investigated. As predicted a word length effect was found, with bi-syllabic words being recalled better than words of three to five syllables length in accordance with Baddeley's (1975) idea that span is word-length -dependent. Moreover, bi-syllabic numbers (i.e. one digit numbers) were found to be recalled better than nouns and proper names of the same length. This difference could be due to the fact that we are more used to recall series of unrelated digits (e.g. when memorising a phone number) than we are to recall series of unrelated words. This could lead to an advantage of recalling (single digit) numbers over words. The prediction that the longer numbers (i.e. two-digit numbers) would be recalled worse than longer words (i.e. nouns and proper names) was confirmed for numbers compared to nouns (i.e. nouns were recalled better than numbers) but it was not found when comparing numbers to proper names. This may suggest that, as hypothesised, the greater semantic and syntactic complexity of two-digit numbers compared to long nouns makes them more difficult to correctly recall. The fact that this difference was not found when comparing two-digit numbers with longer proper names, though, is more difficult to explain. Words from different categories carry distinctive characteristics such as strength of imagery, and frequency of occurrence (Sommers, 1998). These differences are reflected in people's memory (e.g. semantically related nouns and semantically related verbs versus semantically unrelated nouns and verbs). Characteristics of classes of words that could impact on recall could therefore be frequency, semantic meaning/relatedness, and concreteness/imageability. In terms of frequency, the more frequent a particular class of words is, the easier it is to classify these words, to remember them, and to associate them with one another. In this study it could be argued that all three categories used (i.e. nouns, numbers and proper names) are quite frequent, although it is possible that people would not encounter proper names (and in particular the longer ones used in the 3/5 syllables condition in this study) with the same frequency as the nouns and numbers used in this study, although there is no evidence suggesting that this is the case. In terms of semantic meaning, both nouns and numbers carry more meaning than proper names (Frege, 1960), and therefore this could be a mediating factor in reducing the differences in recall performance between two-digit numbers and proper names. Another potential mediating factor is imageability. According to Paivio's Dual Coding Theory (DCT) (1991; 1994), human behaviour and experience can be described in terms of dynamic associative processes that operate on a network of modality-specific verbal and nonverbal (or imagery) representations. According to this theory, words can be remembered through verbal encoding and image encoding. This can explain why, for example, highly imageable concrete nouns are more easily remembered than verbs and other word categories. According to the DCT, the effect of concreteness/imageability is independent of the effect of semantic relatedness. Recall of imageable and non imageable words during a task of word pairs retrieval has been also found to be associated with activity in different brain areas (Fletcher, Shallice, Frith, Frackowiak, & Dolan, 1996). In terms of imageability, among the categories of items used in this study, proper names are less imageable than nouns (that were selected for high imageability). If this was the case, though, performance on span tasks with proper names would be expected to be worse than performance with nouns, and this was not found in the present study. One reason could be that people were using a strategy to associate the names with people they know, but this was not investigated in the present study.

Table 2. 4: Span tests - predictions and results

		PREDICTIONS	RESULTS
STIMULUS		No=N=PN (?)	No>N No>PN N=PN
LENGTH		2 syll>3/5 syll	2syll>3/5syll
STIMULUS X LENGTH	2 syllables	No=N No=PN N=PN	No>N No>PN N=PN
	3/5 syllables	No<N No<PN N=PN	No<N No=PN N=PN

Key: No=Number; N=Noun; PN=Proper names; > = better performance; < = worse performance

A second aim of this study was to investigate the different processes that may be involved in an updating task. In particular, maintenance and control processes, which are thought to be involved in the updating of information and the inhibition of irrelevant information respectively, were investigated. Morris and Jones (1990) have suggested that these two processes are likely to involve specific components of WM, and in particular the CE (Morris & Jones, 1990). The authors also suggested that the CE system is able to re-use its resources very rapidly (e.g. to coordinate complex cognitive processes) and that one way to study this system in isolation from the other subsystems, is to use demanding dynamic memory tasks. This was attempted in the present study, integrating this notion of updating with Palladino et al.'s (2001) idea of updating as a complex process of gradual regulation of the activation level of representations. According to their view, the study of the updating process requires distinguishing between two main aspects of it: the creation of a new representation and the suppression of an old representation. These two aspects were investigated in the present updating task by investigating the correct recall performance and the errors produced, respectively. More specifically, it was proposed that the rate of correct recall would inform as to the level of functioning of the updating process, whereas the presence of intrusion errors would elucidate the functioning of the suppression mechanism. According to Palladino et al. (2001), old contents which have not been completely suppressed and incoming irrelevant information can both interfere with currently relevant contents, by widening the number of possible candidates to be retrieved. In the current study previous list intrusion errors were thought to be due to the intrusion of old not suppressed information from LTM, and same list intrusion errors were thought to be due to either a failure in inhibiting incoming irrelevant information or to the intrusion of information from the same list not completely suppressed.

The main predictions and results on the Updating task are illustrated in Table 2.5. The results show that recall performance on the updating task is affected by load on maintenance: performance was better when fewer items had to be recalled. The pattern of decrease in recall performance with increased load on maintenance suggests that there is a threshold for the number of items that WM can hold and manipulate efficiently, at any one time. Beyond that threshold, performance drops abruptly. Recall performance is also affected by load on control processes, with better performance when fewer items have to be suppressed/inhibited. These results are consistent with the predictions of this study and suggestions that success in remembering relevant information and in suppressing irrelevant information in WM is related to the availability of resources to the WM system (Engle et al., 1992; Conway et al., 1999). Another interesting result within recall performance, is that load on maintenance and on control processes interact with each other. Recall performance is poorer when a high load is imposed on control processes only when the load on maintenance was also highest. This suggests that, when the information to manipulate does not exceed a threshold (which appears to be three items), the CE has enough resources to efficiently hold, manipulate and inhibit information at the same time, even when there is a great deal of incoming information to be inhibited. Past that threshold, the CE becomes more sensitive to the load on control processes and performance tends to drop if the resources available for both processes are taxed.

Table 2. 5: Updating task- predictions and results

		PREDICTIONS	RESULTS
RECALL	INHIBITION	LI>HI	LI>HI
	RECALL	Linear decrease	Quadratic decrease
	STIMULUS	W>N	W>N
	INH X REC	LI>HI with high load on maintenance	LI>HI with R4
S.L. INTRUSIONS	INHIBITION	LI>HI	LI>HI
	RECALL	n.s.	n.s.
	STIMULUS	n.s.	n.s.

Key: LI=Low Inhibition; HI=High Inhibition; R1, R2, R3, R4=1 item to recall, 2 items to recall etc.; W=Words (i.e. nouns); N=Numbers; > = better performance (i.e. more items recalled or fewer errors); < = worse performance (i.e. fewer items recalled or more errors); Decrease= decrease in performance (i.e. decrease in recall or increase in errors); n.s. = not significant

Another prediction of the study was that the production of same list intrusion errors would only be affected by the load on control processes. This was confirmed by the results of the study, as summarised in Table 5, and it supports the validity of this variable as a measure of the functioning of the suppression/inhibition mechanism of the CE. Another interesting finding is that omission errors, like recall performance and production of same list intrusion errors, are affected by load on control processes, with more items being omitted when the load on inhibition is higher. This suggests that when fewer resources are available to the suppression/inhibition mechanism, the participant tends to produce either a representation that should have been inhibited, or cannot produce any representation at all.

Furthermore, the prediction that recalling nouns would be easier than recalling numbers is confirmed by the results. Predictably, this is also reflected in the production of errors: more previous list and invention errors are produced recalling numbers than nouns. This effect is present when the load on maintenance process is higher and, under this condition, is also found with omission errors. These results can be explained by the greater semantic and syntactic complexity (and similarity) of two digit numbers compared to the nouns used in the study. These stimuli were necessary in order to have a big enough pool of number-words to be compared with the nouns used in the study, but may limit any conclusions. It is also possible that more errors are produced with numbers than with nouns because, being two-digit number words formed by a decade and a unit, and there being a limited amount of potential units, participants had active representations containing the same units than had previously been suppressed, and this is likely to have caused confusion (hence the recall of incorrect representations). The counterpart of worse recall performance with numbers is an increase of previous list intrusions and inventions (i.e. representations meant to be previously suppressed or representations never been activated during the task). This latter finding is consistent with the idea that the semantic and syntactic similarity of number-words is a major cause of confusion and therefore a major source of errors. It is interesting to note that with the highest load on maintenance, omission errors are more common with numbers than with words. If there is, as suggested above, a threshold for the number of items that WM can hold and manipulate efficiently at once, past that threshold the drop in performance would seem to be more evident when the material to be recalled is more complex and similar in nature (i.e. two-digit numbers), as this would pose additional load on the maintenance processes, decreasing the performance even further.

In summary, the data from this study add to our understanding of the different processes of WM in general, and more specifically with respect to maintenance and control processes, which are thought to be involved in the updating of information and the inhibition of irrelevant information respectively. Moreover, this study allowed developing and validating an instrument to evaluate updating and inhibition processes of WM. In the following chapters, this test will be used to investigate groups of participants hypothesised or reported to have specific impairments in different WM processes.

CHAPTER 3: CONTROL AND MAINTENANCE PROCESSES IN WORKING MEMORY: THE EFFECTS OF AGEING

The aim of this study was to further investigate the processes studied in the previous experiment, with particular attention to the effects of age on performance in both span tests and updating task.

3.1. Introduction

"Every human capacity after initial growth attains a maximum and then begins to decline. This decline is at first very slow but after a while increases perceptibly" (Wechsler, 1958). According to Wechsler the "maximum growth" is usually attained in the mid-twenties, then between the ages of thirty and sixty the decline tends to be linear. Aging is a process that we all go through and that affects several aspects of our life. One of the consequences involves the cognitive functions, attention and memory among the most affected. Several studies investigating WM and attention (which, as seen in chapter 1, has been conceptualised by Baddeley (1996) as a function of the Central Executive) have investigated the decrease of these functions with aging.

A wealth of studies has suggested that normal aging reduces the efficiency of the Central Executive component of WM (Salthouse, Rogan, & Prill, 1984; Light & Anderson, 1985; Morris, Gick, & Craik, 1988; Gick, Craik, & Morris, 1988; Mc Dowd & Craik, 1988; Foos, 1989). They have found that performance on tasks requiring increased resource demands is reduced in older participants compared to younger participants. This has been interpreted as caused by a decrease in attention on WM tasks with age. The results of these studies are equivocal, however. For example Morris et al. (1988) have used a dual task technique previously used by Baddeley and Hitch (1977) where a concurrent digit load was accompanied by a sentence verification task. In this task, WM load was manipulated by varying either the concurrent load or the syntactic complexity of the sentence to process. The findings showed that both manipulations of WM load impaired performance, but as far as the effect of age was concerned, only increased syntactic complexity had a greater impact on elderly participants, and no such interaction was found with concurrent digit load. Other studies have failed to find any deficit of the central executive in elderly people, which could suggest that there is only a minor impairment of the central executive with age (Stuss, Stethem, & Poirier, 1987; Puckett & Lawson, 1989; Belleville, Peretz, & Malenfant, 1996). In divided attention tasks, some studies have shown an effect of aging while others have reported only minor effects if any (Hartley, 1992). These inconsistencies are typical of much of the literature on aging (for a review see Craik, Anderson, Kerr, & Li (1995)) which makes aging a very interesting variable to investigate when studying WM, as suggested by Baddeley (1996).

One complication in studying any specific cognitive ability and aging is that most functions decline with age and therefore it is difficult to tap any specific ability while ruling out all other intervening factors. Various authors have tried to explore a single function held to be responsible for the decline shown with aging, investigating processing speed (Salthouse, 1991), general intelligence (Rabbitt, 1983), or reduced inhibition ability (Hasher & Zacks, 1988). Baddeley (1996) reported a series of experiments to evaluate the presence of age-related deficits not attributable to either general intelligence or processing speed. In order to do this, Baddeley obtained measures of these two capacities and used these as a part of a multi-variate analysis. In the paradigm participants had to press a key when they saw a specified stimulus appearing. The attentional demand of the task was manipulated in two ways: the presentation of irrelevant stimuli (in same or different sensory modality) for the participant to ignore; and an occasional instruction to switch between sensory modalities. The results of two initial experiments showed that participants were slower when they had to ignore the irrelevant stimuli, particularly if they were in the same sensory modality. Switching modality also slowed responding. In both cases older participants were slower than younger ones. When IQ was used as a covariate, though, this difference disappeared for all conditions except when participants had to ignore irrelevant stimuli in the same sensory modality as the target stimuli. Another experiment looked in more detail at this effect. In this experiment, only the condition with irrelevant stimuli was used because the switching condition did not produce consistent results. More dimensions were introduced for the interfering stimuli in both auditory and visual conditions. As before, both age and modality of the interfering stimuli had a significant effect. Moreover a multi-variate analysis was conducted with age, intelligence and speed of processing as factors. The finding was that age had a significant impact on performance when the stimulus to ignore was in the same modality as the target, even when controlling for intelligence and speed of processing. Baddeley (1996) suggests that the effects of aging can not be reduced to a slowing in the speed of processing or to a decline in fluid intelligence. These findings are compatible with the idea that aging has an impact on the ability to use inhibition to reduce distraction and to focus attention (Hasher & Zacks, 1988). A general decline in inhibition capacity cannot be assumed from these results as the effect was limited to the condition where the irrelevant stimuli were presented in the same sensory modality as the target. A possible explanation proposed by Baddeley (1996) to account for this effect of irrelevant stimuli on older participants is that with aging the attentional focus becomes less peaked towards the target stimulus, and in the context of a broader distribution of attention, older participants would need to process irrelevant stimuli as potentially relevant before discarding them, hence an increase in the reaction times. This explanation is consistent with the fact that the age difference is less prominent when the target and irrelevant stimuli are presented in different sensory modalities, as for both groups the irrelevant stimuli would fall outside the focus of attention. Baddeley and colleagues (1986; 1991) further examined executive control of WM in normal ageing and in people with DAT and found that in normal ageing there is no effect of dual task as in DAT. Despite a wealth of studies addressing the effect of aging on dual task performance, the findings are inconsistent: many studies have found an effect (Salthouse et al., 1984; Crossley & Hiscock, 1992; Whiting & Smith, 1997; Li, Lindenberger, Freund, & Baltes, 2001) but many others have failed to find it (Somberg & Salthouse, 1982; Wickens, Braune, & Stokes, 1987; Tun & Wingfield, 1994; Nyberg, Nilsson, Olofsson, & Bäckman, 1997).

Another set of studies investigated age-related differences in updating WM. Van der Linden, Bredart and Beerten (1994) used a running memory task and found that there was an age effect only when the memory load used was close to the memory span. An interaction was only present with list length but not with serial position (participants were asked to recall items strictly in serial order). Their findings showed that when there are sufficient resources available, updating processes work normally in older participants. The authors suggest that the results support the hypothesis that in older participants central executive resources decrease, and that this is related to a reduction in the processing resources of the central executive more than to its storage capacity. This result is in contrast with Parkinson's (1980) finding that age interacted with serial position in a running memory task, suggesting that storage capacity declines with age. Van der Linden et al. (1994) suggest that the difference in findings may be due to Parkinson's participants being much older than those in their study and to the fact that there was no obvious consideration of the education or intelligence level of Parkinson's participants. Hasher and Zacks (1988) explained the poor performance of older adults in WM tasks using an inhibition/suppression framework that sees inhibitory processes as essential in controlling the information that accesses WM. In particular, they describe control as the efficient inhibition of irrelevant information and suppression of once relevant but currently irrelevant information. The authors suggest that these processes are essential for optimal WM functioning, which, given its limited resources, requires a constant update of the information held and manipulated. The authors argue that the elderly have difficulty inhibiting irrelevant information and in suppressing no longer relevant stimuli. This is supported by De Beni and Palladino's (2004) findings that older adults produce more intrusion errors in tasks requiring them to update relevant and inhibit/suppress irrelevant information, particularly with increasing updating demands.

The discrepancies found in the literature investigating the effects of aging on WM leave this an interesting experimental question. The study presented below attempted to study the effects of aging on performance on an updating task where both load on maintenance and inhibition processes were used as variables.

3.1.1. Hypotheses

This study investigated the processes studied in the previous experiment, with attention to the effects of age on performance in both memory tasks (i.e. span tests and updating task). The possibility that ageing might selectively affect specific components of WM was investigated.

Baddeley (1996) suggested that the level of performance on the digit span forward, which was argued to involve relatively little complex processing, would be determined primarily by storage rather than executive function (although he suggested that the demands made on the central executive will increase as the digit load increases past capacity). The central executive component of WM has been argued to play an important role in the performance of backward span. The idea that there is an age-related decline in central executive function is under investigation here, but it was predicted that in the span backward task, where the demands on maintenance are coupled with demand on control processes, performance of elderly participants would not be necessarily affected because of their hypothesised spared control processes.

Van der Linden et al. (1994) argued that central executive resources decrease with aging and that this has to do with a reduction in the processing resources of the central executive more than to its storage capacity. This idea is consistent with De Beni and Palladino's findings (2004) that older adults produced greater number of intrusion errors, particularly when the updating demand was increased (suggesting an impairment in suppression and inhibition mechanisms), although the authors also suggest a reduction in memory capacity resources with old age. According to Baddeley (1986) however, ageing would provoke a decrease in the "total processing capacity" of the CE, but not in its "flexibility". Baddeley's conceptualisation of "capacity" of the CE is not very clear, and he later abandoned the concept of a storage capacity of the central executive (Baddeley, 1993). Therefore, the term "processing capacity" is interpreted here as a measure of the maintenance processes of WM, which is the amount of information that can be held at any one time in order to be manipulated (or "processed"). This is similar to the concept of capacity of WM, or the focus of attention's capacity in Cowan's model (1999; 2004; 2005) If the effects of ageing on WM were as predicted by Baddeley in 1986 (1986), we would expect a decrease in performance with ageing only in recall in the updating task, but no increase in the number of same list intrusion errors produced. The failure to update relevant information could be in fact due to a reduction in processing capacity, but, assuming that control processes are intact, there should be no difficulty in inhibiting irrelevant information. In contrast, if Van der Linden's interpretation is correct, in older adults we would expect an increase of intrusion errors but not necessarily a decrease in recall performance, in accordance with De Beni and Palladino's (2004) findings.

Hypothesising in accordance with Baddeley (1986), that a CE executive defect in ageing would be related to its total processing capacity and not to its flexibility, the predictions for this study were:

a) No differences in the span tests;
b) A decrease in recall performance (maintenance) with ageing, but no decrease in the ability to inhibit irrelevant information and therefore no increase in the production of errors due to the recall of an item "to be inhibited" (control);

c) A stronger effect of load on maintenance processes in elderly people compared to their controls;

d) A decrease of performance was expected in the group of elderly compared to their controls, but no difference was anticipated between young adults and adults;

e) The main effects found in chapter 2 were expected to be replicated in both span and updating tasks.

3.2. Method

3.2.1. Participants

Ageing is a continuous process. All the above predictions were therefore tested comparing groups of three different age levels (young adults: 19-30 years of age; adults: 34-55 years of age; and elderly: 61-85 years of age) in order to investigate at what point during ageing differences could be noticed.

Fifty-two healthy adults took part in this study (27 males and 25 females). They were divided into four groups, depending on age and years of education. A group was composed of fifteen young adults (YA), aged between 19 and 30 years of age with 13 to 17 years of education. Another group consisted in twelve adults (AE), aged from 34 to 55 years of age matched with the previous group for level of education. A third group was formed by fifteen elderly (E), aged from 61 to 85 years of age with 4 to 17 years of education. Another group consisted in ten adults (A), aged from 37 to 54 years of age matched with the previous group for level of education. Table 3.1 illustrates participants' age and education in the four groups.

Table 3. 1: Participants' age and education

	Mean (Standard Deviation)			
	YA (N=15)	AE (N=12)	E (N=15)	A (N=10)
Age	23.9 (2.52)	47.2 (6.82)	71.3 (7.48)	44.3 (5.06)
Education	15.9 (1.10)	16.7 (0.49)	7.5 (4.16)	8.0 (0.00)
Male:Female Ratio	11:4	5:7	6:9	5:5

3.2.2. Experimental Task

3.2.2.1. Span tests

The same stimuli and procedures were used as in the study on healthy participants (see Chapter 2).

3.2.2.2. Updating Task

The same stimuli and procedures were used as in the study on healthy participants (see Chapter 2).

3.3. Results

Since the groups had different levels of education, an initial analysis was run to investigate the effects of education. A between-subjects multivariate Analysis of Variance was performed with EDUCATION as between-subjects independent variable with two levels (LOW, with 4 to 9 years of education; and HIGH, with 10 to 17 years of education). The dependent variables investigated were the performances in the various span tests and the total recall performance on the Updating task. The results show that, when including AGE as a covariate, no difference was found in any of the span tests requiring recalling short (i.e. bi-syllabic) items[27], nor in the total recall in the updating task[28]. In contrast, significant differences were found in performance on the digit span tests requiring the recall of longer items (2-digit span [$F_{(1,48)}= 6.85$; $p<0.02$]; 3-5 syllable nouns

[27] digit span [$F_{(1,48)}= 3.29$; $p>0.05$]; 2-syllable nouns span [$F_{(1,48)}= 2.07$; $p>0.05$]; 2-syllables proper names span [$F_{(1,48)}= 1.25$; $p>0.05$]); digit span backwards [$F_{(1,48)}= 3.09$; $p>0.05$]

[28] [$F_{(1,48)}= 0.66$; $p>0.05$]

span [$F_{(1,48)}$= 4.41; p<0.02]; 3-5 syllable proper names span [$F_{(1,48)}$= 8.24; p<0.02]), with the group with higher level of education recalling more items than the group with lower level of education.

In all subsequent analyses the group of young adults was compared to the group of adults matched for education, and the group of elderly was compared to the group of adults matched for education. This was to ensure that differences found between groups were not attributable to the education level of the participants.

3.3.1. Span tests

3.3.1.1. Young adults and adults with higher education

A 2X3X2 mixed design ANOVA was performed in order to investigate the difference between groups in the span tests, comparing the recall of items of different length (bi-syllabic items or 3/5 syllables items) and of different categories (i.e. numbers, objects and animals, and proper names). The between-subjects independent variable was GROUP with two levels (YA – young adults; and AE – adults educated). The within-subjects independent variables were STIMULUS with three levels (NUMBER, when the stimulus to recall was a number; NOUN, when the stimulus to recall was a name of object or animal; PROPER NAME, when the stimulus to recall was a proper name), and LENGTH with two levels (2-SYLL and 3/5-SYLL). The dependent variable was the number of items correctly recalled in the correct order. Bonferroni correction was used when multiple comparisons were performed on the data, and all the significance values reported include this correction where necessary.

A statistically significant main effect was found for GROUP [$F(1,25) = 15.27$; $p<0.002$], due to the group of young participants recalling significantly more items than the group of adults matched for education.

The main effect of STIMULUS is significant [$F(2,50) = 9.94$; $p<0.001$]. This was investigated conducting a Paired Samples t-test comparing each of the three levels of the variable with the others. The results show that in the conditions with numbers to recall the performance is significantly better than the performance with nouns to recall [$t(26) = 2.62$; $p<0.05$], and proper names[$t(26) = 4.53$; $p<0.005$]. The last two conditions do not significantly differ one from the other[29].

The main effect of LENGTH is also significant [$F(1,25) = 86.84$; $p<0.001$], due to the performance on the condition with bi-syllabic items being better than in the condition with longer items to recall.

A significant interaction was found for STIMULUS X LENGTH [$F(2,50) = 27.47$; $p<0.001$][30]. A Paired Samples t-test was performed comparing, for each level of LENGTH, each level of STIMULUS with the others. As illustrated in Figure 3.1, the results show that in the 2-SYLL condition of LENGTH, the digit span is significantly longer than the span with nouns [$t(26) = 7.15$; $p<0.01$], and proper names [$t(26) = 7.21$; $p<0.01$]. The difference between the latter two was not significant[31]. In the 3/5-SYLL condition of LENGTH, no significant difference was found between levels of STIMULUS[32].

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[29] [$t(26) = 1.95$; $p>0.05$]

[30] No significant interaction was found for STIMULUS X GROUP[$F(2,50) = 0.33$; $p>0.05$], LENGTH X GROUP [$F(1,25) = 0.72$; $p>0.05$], and STIMULUS X LENGTH X GROUP [$F(2,50) = 0.76$; $p>0.05$].

[31] [$t(26) = 0.62$; $p>0.05$]

[32] 3/5-SYLL NUMBER vs. 3/5-SYLL NOUN [$t(26) = -2.15$; $p>0.05$], 3/5-SYLL NUMBER vs. 3/5-SYLL PROPER NAME [$t(26) = -0.19$; $p>0.05$], 3/5-SYLL NOUN vs. 3/5-SYLL PROPER NAME [$t(26) = 1.95$; $p>0.05$]

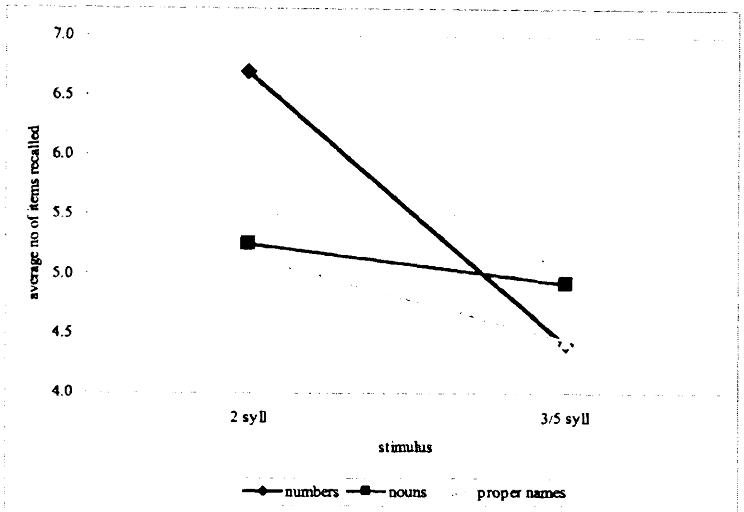

Figure 3. 1: Span tests - (YA and AE) - interaction STIMULUS X LENGTH

A one-way between-subjects ANOVA was performed to compare the performance on the digit span backwards in the two groups. The between-subjects independent variable was GROUP with two levels (YA and AE) and the dependent variable was the number of items recalled by the participants in the digit span backwards test.

The results show a significant main effect of GROUP [$F(1,25) = 6.35$; $p<0.02$]. This difference is due to the group of young participants performing better than the group of adults.

3.3.1.2. Adults and elderly with lower education

Another 2X3X2 mixed design ANOVA was performed in order to investigate the difference between the other two groups in the span tests, comparing the recall of items of different length (i.e. bi-syllabic items or 3/5 syllables items) and of different categories (i.e. numbers, objects and animals, and proper names). The between-subjects independent variable was GROUP with two levels (E – elderly; and A – adults). The within-subjects independent variables and the dependent variable were the same as in the previous study. Bonferroni correction was used when multiple comparisons were performed on the data, and all the significance values reported include this correction where necessary.

A statistically significant main effects was found for STIMULUS [$F(2,44) = 4.23$; $p<0.05$]. A Paired Samples t-test compared each of the three levels of the variable with the others. As Figure 3.2 illustrates, the results show that in the conditions with numbers to recall the performance is significantly better than the performance with proper names [$t(23) = 3.30$; $p<0.02$]. No statistical difference was found between recalling numbers and recalling nouns[33], or between recalling nouns and recalling proper names[34].

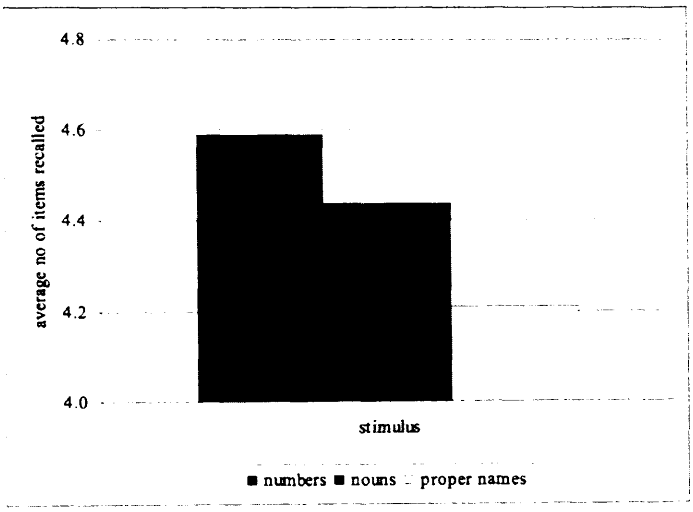

Figure 3. 2: Span tests - (A and E) - main effect of STIMULUS

The main effect of LENGTH is also significant [$F(1,22) = 133.74$; $p<0.001$], and this is due to the performance on the condition with bi-syllabic items being better than on the condition with longer items to recall.

No significant main effect of group was found[35].

A significant interaction was found for LENGTH X GROUP [$F(1,22) = 12.22$; $p<0.005$] [36]. A between-subjects ANOVA was performed comparing the

[33] [$t(23) = 1.13$; $p>0.05$]
[34] [$t(23) = 1.66$; $p>0.05$]
[35] [$F(1,22) = 3.28$; $p>0.05$]

performance of the two groups at the two different levels of LENGTH. The independent variable was GROUP with two levels (E an A) and the dependent variables were the number of items recalled in the correct order when the items were 2-syllables long (2-SYLL) and when the items were 3 to 5 syllables long (3/5-SYLL). Figure 3.3 illustrates the results, showing that the two groups perform differently only when the items to recall are bi-syllabic [$F(1,22) = 7.07$; $p<0.02$][37].

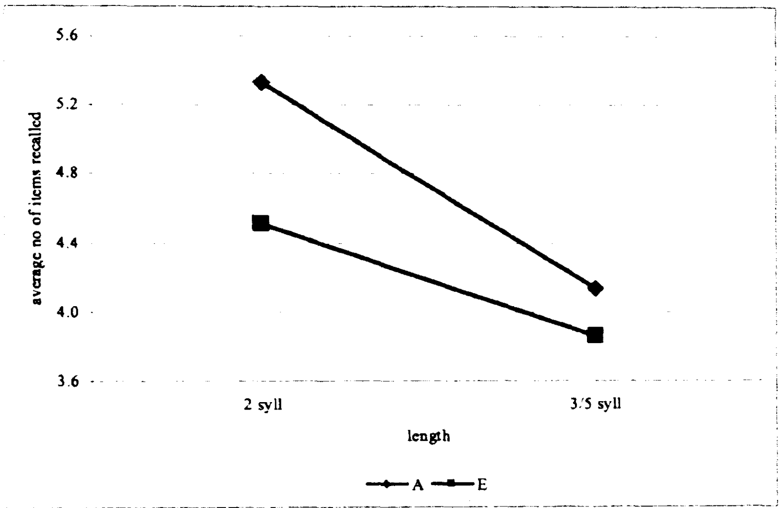

Figure 3. 3: Span tests - (A and E) - interaction LENGTH X GROUP

The interaction STIMULUS X LENGTH is statistically significant [$F(2,44) = 42.22$; $p<0.001$]. A Paired Samples t-test was performed comparing, for each level of LENGTH, each level of STIMULUS with the others. The results, illustrated in Figure 3.4, show that in the 2-SYLL condition of LENGTH, the digit span is significantly longer than the span with nouns [$t(23) = 5.94$; $p<0.01$], and proper names[$t(23) = 5.84$; $p<0.01$][38]. In the 3/5-SYLL condition of LENGTH,

[36] The interaction STIMULUS X GROUP was not statistically significant [$F(2,44) = 0.11$; $p>0.05$].
[37] No difference in performance when the items were three to five syllables long [$F(1,22) = 0.75$;$p>0.05$]
[38] The difference between 2-SYLL NOUN and 2-SYLL PROPER NAME, was not significant [$t(23) = -1.37$; $p>0.05$].

the two-digit span (i.e. 3/5-SYLL NUMBER) is significantly shorter than the span with nouns [$t(23) = -4.63$; $p<0.01$], and proper names [$t(23) = -4.51$; $p<0.01$][39].

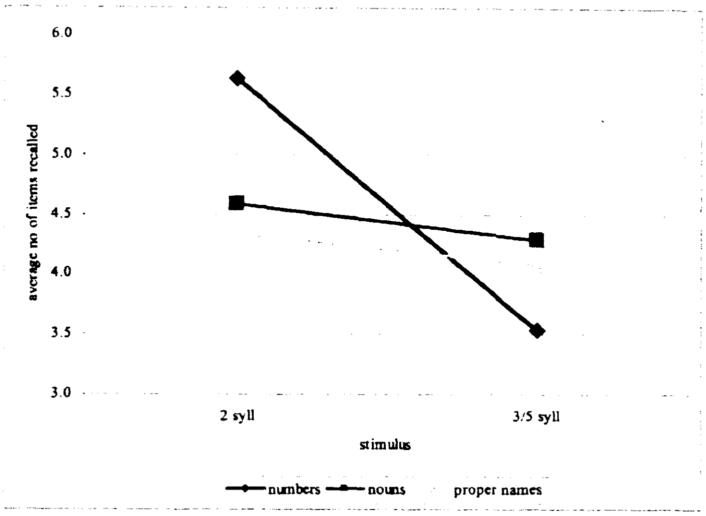

Figure 3. 4: Span tests - (A and E) - interaction STIMULUS X LENGTH

Stimulus and length also interacted with group, as demonstrated by the significant STIMULUS X LENGTH X GROUP interaction [$F(2,44) = 5.44$; $p<0.1$]. This was investigated conducting the same analysis described above, in each group. The results, illustrated in Figure 3.5, show that only in the group of elderly the differences found above are significant[40]. No significant difference was found in the adults group[41].

[39] The difference between 3/5-SYLL NOUN and 3/5-SYLL PROPER NAME, was not significant [$t(23) = 1.31$; $p>0.05$].
[40] More specifically, in the 2-SYLL condition of LENGTH, the digit span was significantly longer than the span with nouns [$t(13) = 5.09$; $p<0.01$], and proper names [$t(13) = 6.90$; $p<0.01$]. The difference between nouns and proper names, was not significant [$t(13) = 1.59$; $p>0.05$]. In the 3/5-SYLL condition of LENGTH, the two-digit span was significantly shorter than the span with nouns [$t(13) = -3.71$; $p<0.05$], and proper names [$t(13) = -6.0$; $p<0.01$]. The difference between the latter two, was not significant [$t(13) = 0.00$; $p>0.05$].
[41] 2-SYLL NUMBERS vs. 2-SYLL NOUNS [$t(9) = 3.21$; $p>0.05$]; 2-SYLL NUMBERS vs. 2-SYLL PROPER NAMES [$t(9) = 2.21$; $p>0.05$]; 2-SYLL NOUNS vs. 2-SYLL PROPER NAMES [$t(9) = 0.32$; $p>0.05$]; 3/5-SYLL NUMBERS vs. 3/5-SYLL NOUNS [$t(9) = 3.21$; $p>0.05$]; 3/5-SYLL NUMBERS vs. 3/5-SYLL PROPER NAMES [$t(9) = -1.0$; $p>0.05$]; 3/5-SYLL NOUNS vs. 3/5-SYLL PROPER NAMES [$t(9) = 2.24$; $p>0.05$]

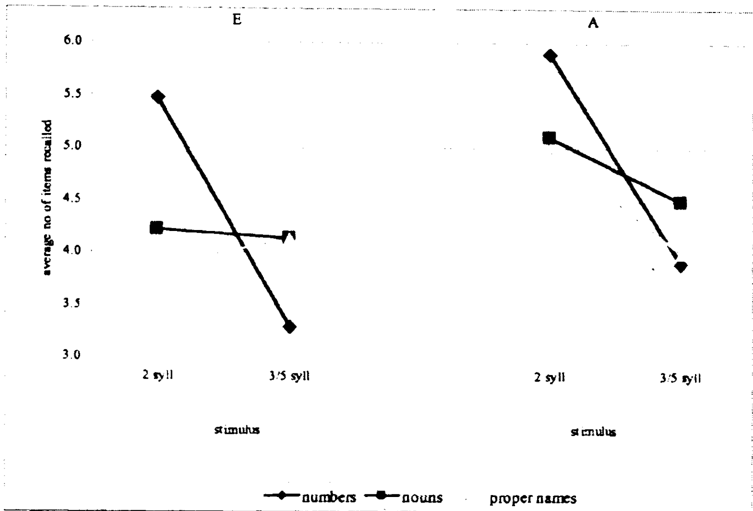

Figure 3. 5: Span tests - (A and E) - interaction STIMULUS X LENGTH in the group of elderly (left) and in the group of adults (right)

A one-way between-subjects ANOVA was performed to compare the performance on the digit span backwards in the two groups. The between-subjects independent variable was GROUP with two levels (E and A) and the dependent variable was the number of items recalled by the participants in the digit span backwards test. The results showed no significant main effect of GROUP[42].

3.3.2. Updating task

In the Updating task, the group of young adults (YA) was compared to the group of adults matched for level of education (AE), and the group of elderly (E) was compared to the group of adults (A) matched for education. Separate analyses were performed in order to compare these two pairs of groups.

Separate ANOVAs were performed in order to investigate: recall performance (measured as the percentage of correct recall); the production of errors of intrusion of items from the same list; the production of errors of intrusion of items presented in a previous list; the production of items invented by the

[42] [$F(1,23) = 0.29$; $p>0.05$]

participant; and the omissions. Errors were measured as the percentage of items incorrectly recalled (or omitted) in place of correct items.

Bonferroni correction was used when multiple comparisons were performed on the data, and all the significance values reported include this correction where necessary.

3.3.2.1. Correct recall

YOUNG ADULTS AND ADULTS WITH HIGHER EDUCATION

A 2x2x4x2 mixed design ANOVA was conducted to assess differences in recall performance between the group of young adults and the group of adults matched for education, across conditions.

The between-subjects independent variable was GROUP with two levels (YA and AE). The within-subjects factors were: STIMULUS with two levels (NOUN and NUMBER), RECALL with four levels (R1, R2, R3, R4), and INHIBITION with two levels (LI and HI). The dependent variable was the percentage of correctly recalled items.

The analyses reveal a significant main effects of GROUP [$F(1,25) = 6.11$, $p<0.05$], explained by the group of young adults recalling more items than the group of adults.

The main effect of INHIBITION is also significant [$F(1,25) = 29.95$, $p<0.001$]. This effect is explained by a worse performance on recall when the load on control processes is higher (HI) compared to when the load on control processes is lower (LI).

The analyses also reveal a main effect of RECALL [$F(2,45) = 76.70$, $p<0.001$]. A polynomial contrast confirmed that this is better accounted for by a quadratic[43] decrease [F(1,25) = 54.89; p<.0.001]. This is illustrated in Figure 3.6, where a little difference can be seen between one and two items to recall, but larger differences can be observed between two and three items and between three and four items.

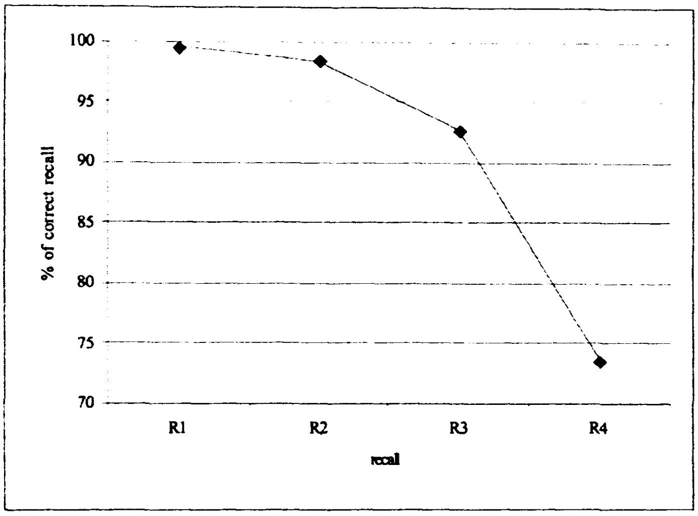

Figure 3. 6: Updating task - Correct recall - (YA and AE) - main effect of RECALL

The main effect STIMULUS is significant [F(1,25) = 45.68, p<0.001], due to the performance of recall with numbers being significantly worse than the performance with words.

The interaction RECALL X STIMULUS is significant [F(2.54) = 35.72, p < 0.001][44]. A paired Samples t-test was conducted for each level of RECALL, comparing the performance at the different levels of STIMULUS (i.e. noun and number). As shown in Figure 3.7, the difference between the two levels of

[43] A linear decrease was also found to be significant [F(1,25) = 110.04; p<.0.001].
[44] The other interactions were not significant (INHIBITION X GROUP [F(1,25) = 2.30, p>0.05]; RECALL X GROUP [F(2,45) = 2.39, p p>0.05]; STIMULUS X GROUP [F(1,25) = 0.32, p>0.05]; INHIBITION X RECALL [F(2,40) = 2.52, p>0.05]; INHIBITION X RECALL X GROUP [F(2,40) = 0.59, p>0.05], INHIBITION X STIMULUS [F(1,25) = 0.00, p>0.05]; INHIBITION X STIMULUS X GROUP [F(1,25) = 1.17, p>0.05]; RECALL X STIMULUS X GROUP [F(2,54) = 0.40, p>0.05]; INHIBITION X RECALL X STIMULUS [F(2,49) = 0.77, p>0.05]; INHIBITION X RECALL X STIMULUS X GROUP [F(2,49) = 1.35, p>0.05]).

stimulus is only significant when the task requires to recall four items (R4) [t(26)= 9.01, p<0.005], and it is not significant at the other levels[45].

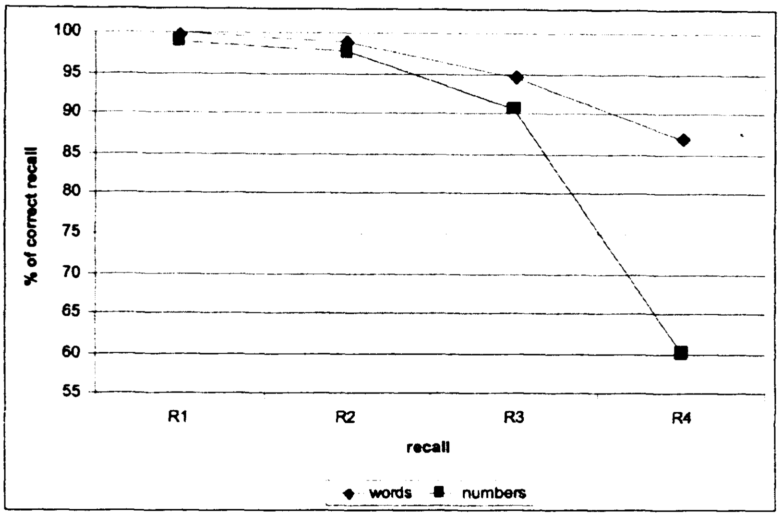

Figure 3. 7: Updating task - Correct recall - (YA and AE) - interaction RECALL X STIMULUS

ADULTS AND ELDERLY WITH LOWER EDUCATION

Another 2X2X4X2 mixed design ANOVA was conducted in order to investigate the difference the in recall performance between the other two groups (elderly and adults matched for education) across conditions.

The between-subjects independent variable was GROUP with two levels (A and E). The within-subjects independent variables and the dependent variable were the same as in the previous analysis.

The analyses revealed a significant main effects of GROUP [F(1,23) = 9.17, p<0.01], explained by the group of adults recalling more items than the group of elderly.

The main effect of INHIBITION is significant [F(1,23) = 24.13, p<0.001] and it is explained by a worse performance on recall when the load on control

[45] R1 [R2 [t(26)= 1.00, p>0.05], R2 [t(26)= 1.14, p>0.05], and R3 [t(26)= 1.61, p>0.05]

processes is higher (HI) compared to when the load on control processes is lower (LI).

The main effect of RECALL is significant [F(2,50) = 103.51, p<0.001] and a polynomial contrast confirms that the factor RECALL is better accounted for by a linear[46] decrease [F(1,23) = 167.23; p<.0.001]. This can be observed in Figure 3.8 where the percentage of correct recall decreases proportionately to the increase in the number of items to recall.

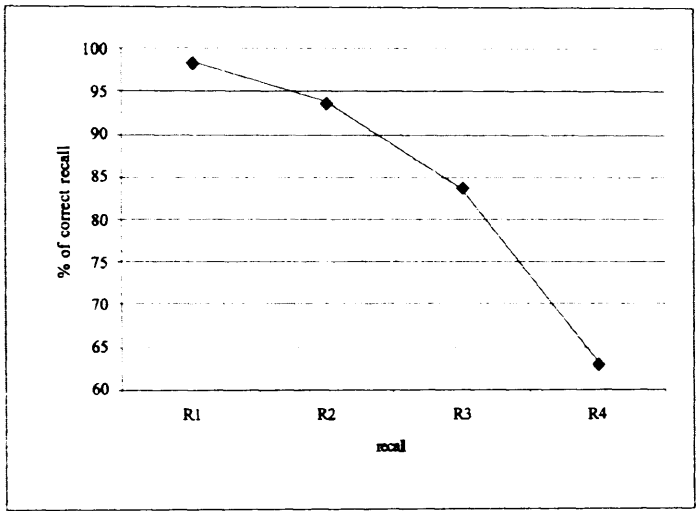

Figure 3. 8: Updating task - Correct recall - (A and E) - main effect of RECALL

The analyses also revealed a significant main effect of STIMULUS [F(1,23) = 80.00, p<0.001], due to the performance of recall with numbers being significantly worse than the performance with words.

The interaction INHIBITION X RECALL is significant [F(3,69) = 6.33, p<0.002]. A Paired Samples t-test was conducted for each level of RECALL, comparing the performance at different levels of INHIBITION (i.e. low and high). As illustrated in Figure 3.9, this analysis show that the difference between low and high inhibition is not significant when the task requires to recall one or two

[46] A quadratic decrease was also found to be significant [F(1,23) = 38.70; p<.0.001].

items[47], but it is significant when it requires to recall three [t(24)= 6.02, p<.005], and four [t(24)= 5.22, p<.005] items.

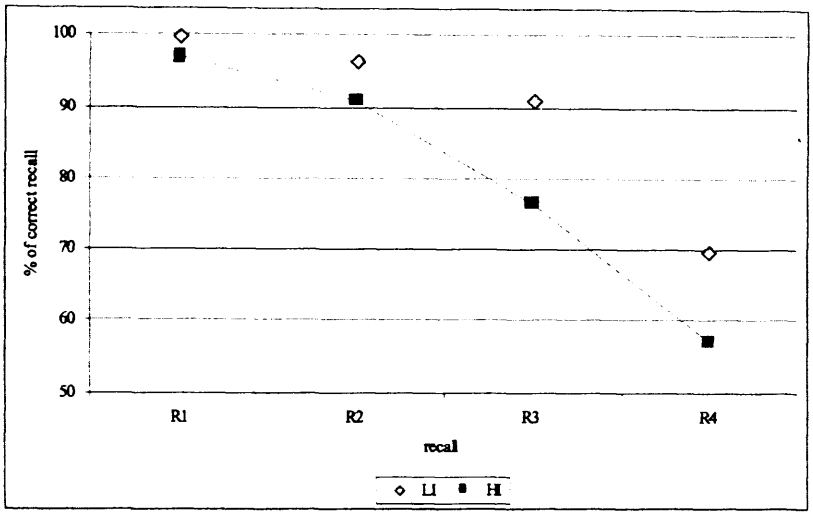

Figure 3. 9: Updating task - Correct recall - (A and E) - interaction INHIBITION X RECALL

Inhibition and recall also interact with stimulus: the interaction INHIBITION X RECALL X STIMULUS is significant [F(2,55) = 3.05, p<0.05] and it was further investigated with two separate Paired Samples t-tests, one for each level of STIMULUS (i.e. noun and number), comparing the performance with high and low inhibition at each level of recall. The results, illustrated in Figure 3.10, show that when recalling words, the difference between low and high inhibition is only significant when the task requires to recall four words [t(24)= 6.59, p<.005], but not at any of the other levels[48]. When recalling numbers, the difference between high and low inhibition levels is only significant when the task requires to recall three words [t(24)= 5.02, p<.005] but not at any of the other levels[49].

[47] R1: [t(24)= 1.37, p>0.05]; R2: [t(24)= 1.49, p>0.05]
[48] R1[t(24)= 1.00, p>0.05], R2 [t(24)= 2.87, p>0.05], R3[t(24)= 2.68, p>0.05]
[49] R1[t(24)= 1.46, p>0.05], R2 [t(24)= 0.50, p>0.05], R4[t(24)= 2.09, p>0.05]

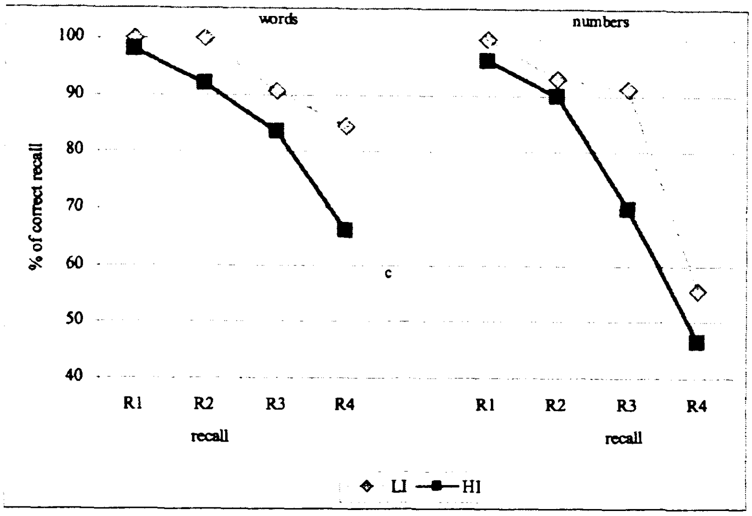

Figure 3. 10: Updating task - Correct recall - (A and E) - interaction INHIBITION X RECALL X STIMULUS

The RECALL X STIMULUS interaction is significant [$F(3,69) = 24.20$, $p < 0.001$]. A paired Samples t-test was conducted for each level of RECALL, comparing the performance at the different levels of STIMULUS (i.e. noun and number). As Figure 3.11 illustrates, this analysis reveals that the difference between the two levels of stimulus is only significant when the task requires to recall four items [$t(24)= 9.98$, $p<0.005$], and it is not significant at the other levels[50].

[50] R1 [$t(24)= 1.00$, $p>0.05$], R2 [$t(24)= 2.09$, $p>0.05$], and R3 [$t(24)= 2.25$, $p>0.05$]

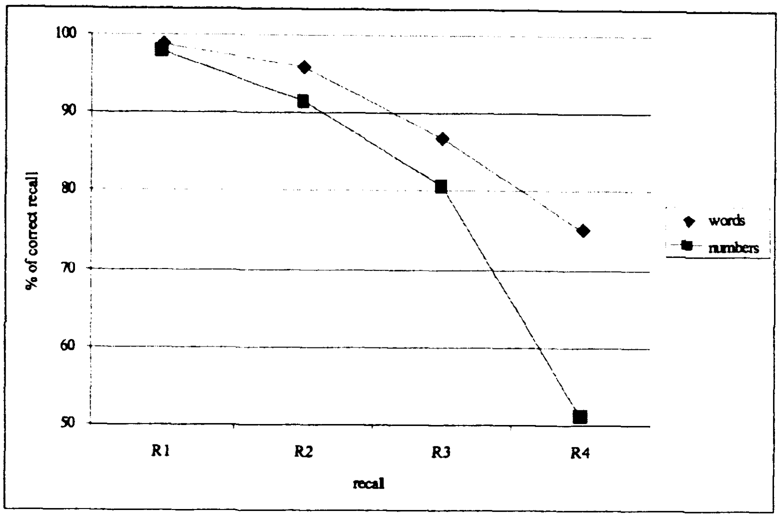

Figure 3. 11: Updating task - Correct recall - (A and E) - interaction RECALL X STIMULUS

Recall and stimulus also interacts with group, as the RECALL X STIMULUS X GROUP interaction is significant [$F(3,69) = 2.96$, $p<0.05$][51] . This was further investigated conducting the same Paired Sample t-test as above in each one of the groups. The results show that in the group of adults the difference between the two levels of stimulus is only significant when the task requires to recall four items [$t(9)= 7.44$, $p<0.005$], and it is not significant at the other levels[52]. Also in the group of elderly the difference between the two levels of stimulus is only significant when the task requires to recall four items [$t(14)= 7.14$, $p<0.005$], and it is not significant at the other levels[53]. The interaction is probably due to the fact that in the group of elderly there is a trend for the difference to be significant also with two and three items to recall.

[51] The other interactions were not significant (INHIBITION X GROUP [$F(1,25) = 2.30$, $p>0.05$]; RECALL X GROUP [$F(2,45) = 2.39$, p $p>0.05$]; STIMULUS X GROUP [$F(1,25) = 0.32$, $p>0.05$]; INHIBITION X RECALL X GROUP [$F(2,40) = 0.59$, $p>0.05$], INHIBITION X STIMULUS [$F(1,25) = 0.00$, $p>0.05$]; INHIBITION X STIMULUS X GROUP [$F(1,25) = 1.17$, $p>0.05$]; and INHIBITION X RECALL X STIMULUS X GROUP [$F(2,49) = 1.35$, $p>0.05$]).

[52] R1 [n.s.: Could not compute the difference since all scores were equivalent], R2 [$t(9)= -1.00$ $p>0.05$], and R3 [$t(9)= 0.35$, $p>0.05$]

[53] R1 [$t(14)= 1.00$, $p>0.05$]; R2 [$t(14)= 2.65$, $p>0.05$]; R3 [$t(14)= 2.83$, $p>0.05$]

3.3.2.2. *Same list intrusion errors*

YOUNG ADULTS AND ADULTS WITH HIGHER EDUCATION

A 2x2x4x2 mixed design ANOVA was conducted to see differences in the production of intrusion errors of items from the same list between the group of young adults (YA) and the group of adults matched for education (AE), across conditions.

The within-subjects independent variables were the same as in the previous analyses. The dependent variable was the percentage of intrusions from the same list (as a proportion of the total number of responses).

The analysis revealed a significant main effects of GROUP [$F(1,25) = 5.82$, $p<0.05$], explained by the group of adults producing more intrusion errors from the same list than the younger group.

The main effect of INHIBITION is also significant [$F(1,25) = 8.28$, $p<0.01$][54], and it is explained by a higher percentage of intrusions from the same list, when the load on control processes is higher (HI) compared to when the load on control processes is lower (i.e. LI).

The interaction INHIBITION X GROUP is significant [$F(1,25) = 4.52$, $p<0.05$]. A between-subjects ANOVA was performed for each level of INHIBITION. The independent variable was GROUP with two levels (YA and AE) and the dependent variable was the percentage of same list intrusions produced. Figure 3.12 shows that the production of same list intrusions is significantly different in the two groups only when the load on the inhibition

[54] No significant main effect of RECALL [$F(3,75) = 1.34$, $p>0.05$] and STIMULUS [$F(1,25) = 0.00$, $p>0.05$] were found.

processes is high [F(1,25) = 6.40; p<0.02], but not when the load on the inhibitory processes is low[55].

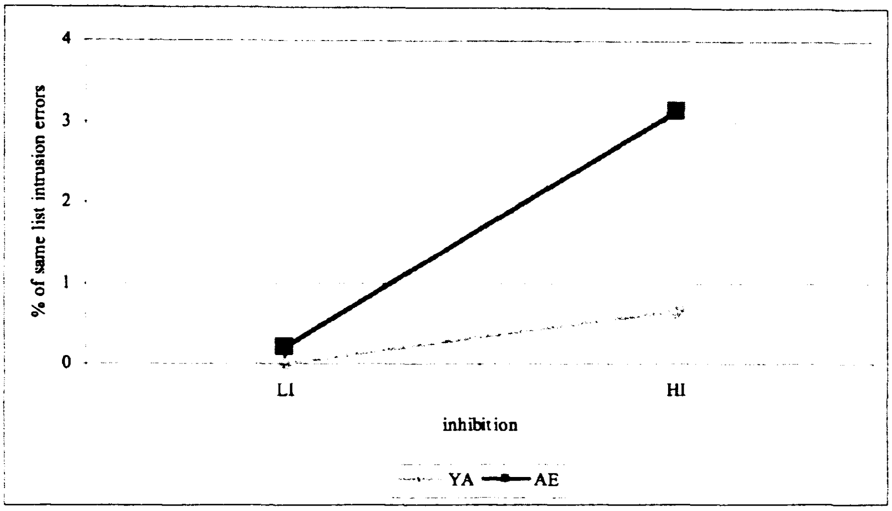

Figure 3. 12: Updating task - Same list intrusion errors - (YA and AE) - interaction INHIBITION X GROUP

The interaction RECALL X STIMULUS X GROUP is significant [F(2,46) = 3.93, p<0.05][56]. In order to analyse this interaction, a between-subjects ANOVA was performed for each level of STIMULUS comparing the performance of the two groups at each level of RECALL. The independent variable was GROUP with two levels (YA and AE) and the dependent variable was the percentage of same list intrusions produced. The results, illustrated in Figure 3.13, show that when recalling words, the group of adults produces significantly more intrusions from the same list than the younger group only when the load on the memory system is higher (R3 [F(1,25) = 6.94; p<0.02]; and R4

[55] [F(1,25) = 1.26; p>0.05]

[56] The other interactions were not significant (RECALL X GROUP [F(3,75) = 0.10, p>0.05], STIMULUS X GROUP [F(1,25) = 1.97, p>0.05], INHIBITION X RECALL [F(3,75) = 0.73, p>0.05], INHIBITION X RECALL X GROUP [F(3,75) = 0.30, p>0.05], INHIBITION X STIMULUS [F(1,25) = 0.18, p>0.05], INHIBITION X STIMULUS X GROUP [F(1,25) = 1.09, p>0.05]; RECALL X STIMULUS [F(3,75) = 2.15, p>0.05], INHIBITION X RECALL X STIMULUS [F(2,42) = 2.34, p>0.05]; and INHIBITION X RECALL X STIMULUS X GROUP [F(2,42) = 3.36, p>0.05]).

[F(1,25) = 8.33; p<0.01]), but not when the load on maintenance is lower[57]. When recalling numbers, the two groups do not significantly differ at any of the levels of recall[58].

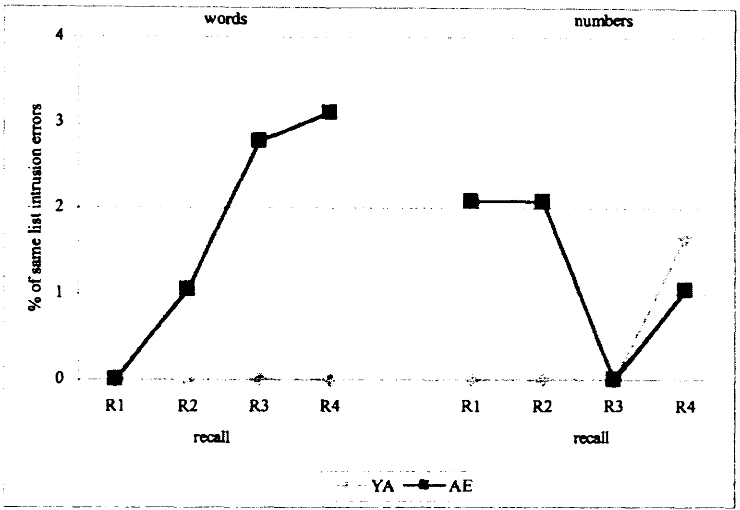

Figure 3. 13: Updating task - Same list intrusion errors - (YA and AE) - interaction RECALL X STIMULUS X GROUP

ADULTS AND ELDERLY WITH LOWER EDUCATION

Another 2X2X4X2 mixed design ANOVA was conducted in order to investigate the differences across conditions in the production of intrusion errors of items from the same list between the group of elderly (E) and the group of adults (A) matched for education .

The within-subjects factors and the dependent variable were the same as in the previous analysis.

The analysis showed that the main effect of INHIBITION is significant [F(1,23) = 15.75, p<0.002], due to a higher percentage of intrusions from the same list being produced when the load on control processes is higher (HI) compared to when the load on control processes is lower (i.e. LI).

[57] R1 [n.s.: Could not compute the difference since all scores were equivalent], and R2 [F(1,25) = 1.26; p>0.05]

[58] R1[F(1,25) = 1.26; p>0.05], R2 [F(1,25) = 2.78; p>0.05], R3 [n.s.: Could not compute the difference since all scores were equivalent], and R4 [F(1,25) = 0.16; p>0.05])

The analysis also reveals a significant main effect of RECALL [$F(3,69) = 6.89$, $p<0.001$], and a polynomial contrast confirms that this is explained by a significantly linear increase [$F(1,23) = 23.82$; $p<.0.001$]. No other significant trends were observed. This is illustrated in figure 3.14, where the percentage of same list intrusion errors increases proportionately to the increase in the number of items to recall.

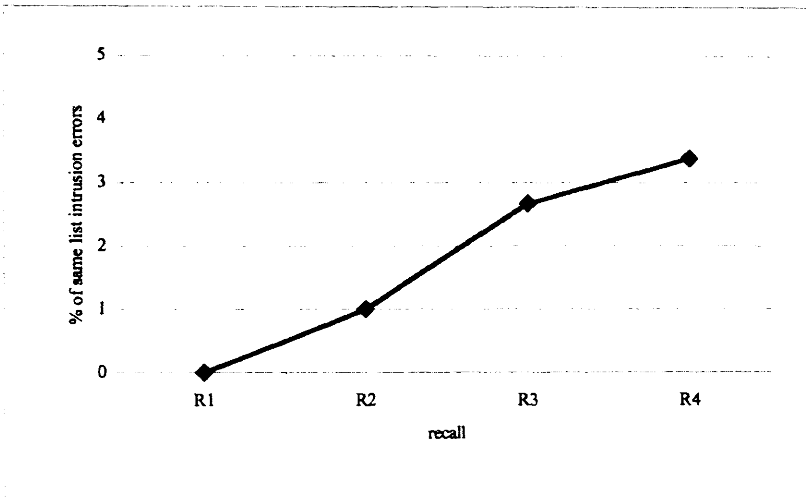

Figure 3. 14: Updating task - Same list intrusion errors - (A and E) - main effect of RECALL

The main effect of STIMULUS is significant [$F(1,23) = 9.47$, $p<0.01$], and it is due to a higher percentage of intrusions from the same list errors being produced with words than with numbers.

No significant main effect of GROUP[59] was found.

The interaction INHIBITION X RECALL is significant [$F(2,42) = 7.44$, $p<0.005$], and a Paired Samples t-test was conducted for each level of RECALL, comparing the performance on the different levels of INHIBITION (low and high). Figure 3.15 illustrates the finding that the difference between low and high

[59] [$F(1,23) = 0.00$, $p>0.05$]

inhibition is only significant when the task requires to recall four items [t(24)= -3.44, p<.01], but not when the items to recall are one, two, or three[60].

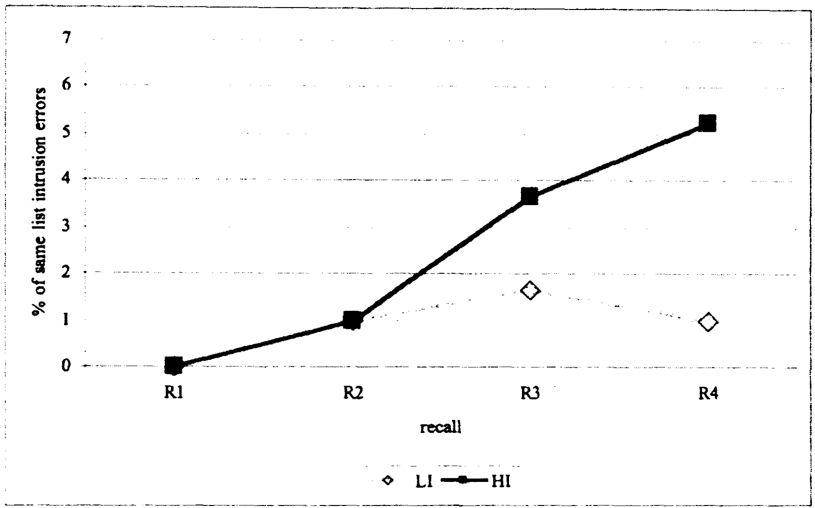

Figure 3. 15: Updating task - Same list intrusion errors - (A and E) - interaction INHIBITION X RECALL

The INHIBITION X STIMULUS interaction is significant [F(1,23) = 8.30, p <0.01], and it was analyzed conducting a Paired Sample t-test for each level of INHIBITION (low and high) comparing the percentage of intrusion errors from the same list at the different levels of STIMULUS (i.e. noun and number). Figure 3.16 shows that the difference between conditions of STIMULUS is significant only with high inhibition [t(24)= 4.03, p<0.005] but not with low inhibition [t(24)= 1.90, p>0.05].

[60] R1: [n.s.: Could not compute the difference since all scores were equivalent]; R2: [t(24)= 0.00, p>0.05]; R3;[t(24)= -2.30, p>0.05]

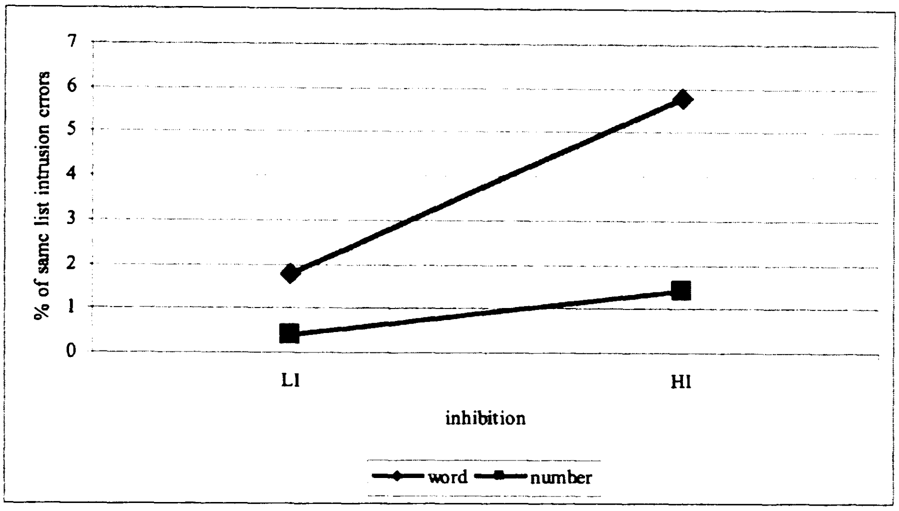

Figure 3. 16: Updating task - Same list intrusion errors - (A and E) - interaction INHIBITION X STIMULUS

A significant interaction RECALL X STIMULUS was also found [$F(2,45) = 7.05$, $p < 0.005$][61], and a Paired Samples t-test was conducted for each level of RECALL, comparing the performance at the different levels of STIMULUS (noun and number). As illustrated in Figure 3.17, this shows that the difference between the two levels of STIMULUS is only significant in the conditions of high load (R3 [$t(24) = -18.42$, $p < 0.005$.], R4 [$t(24) = 3.44$ $p < 0.01$]), but it is not significant in the conditions of low load on maintenance[62].

[61] The other interactions were not significant (INHIBITION X GROUP [$F(1,23) = 0.00$, $p > 0.05$], RECALL X GROUP [$F(3,69) = 0.37$, $p > 0.05$], STIMULUS X GROUP [$F(1,23) = 1.01$, $p > 0.05$], INHIBITION X RECALL X GROUP [$F(2,42) = 0.46$, $p > 0.05$], INHIBITION X STIMULUS X GROUP [$F(1,23) = 0.00$, $p > 0.05$]; RECALL X STIMULUS X GROUP [$F(2,45) = 1.54$, $p > 0.05$]., INHIBITION X RECALL X STIMULUS [$F(2,48) = 0.83$, $p > 0.05$]; and INHIBITION X RECALL X STIMULUS X GROUP [$F(2,48) = 0.91$, $p > 0.05$]).

[62] R1 [n.s.: Could not compute the difference since all scores were equivalent], R2 [$t(24) = -1.45$, $p > 0.05$]

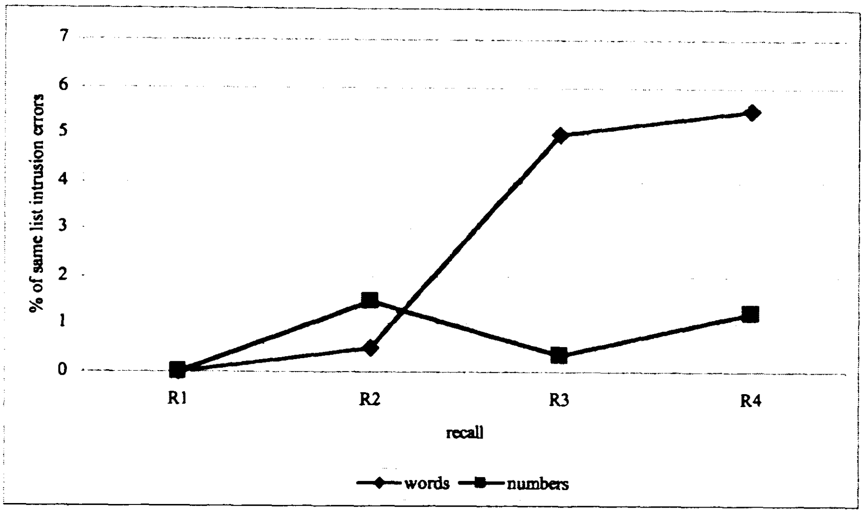

Figure 3. 17: Updating task - Same list intrusion errors - (A and E) - interaction RECALL X STIMULUS

3.3.2.3. Previous list intrusion errors

YOUNG ADULTS AND ADULTS WITH HIGHER EDUCATION

A 2x2x4x2 mixed design ANOVA was conducted to see differences in the production of intrusion errors of items from a previous list between the group of young adults (YA) and the group of adults (AE) matched for education, across conditions.

The same within-subjects independent variables used in the previous analyses were investigated. The dependent variable was the percentage of intrusions from a previous list (as a proportion of the total number of responses).

The analysis reveals that the main effect of INHIBITION is significant [$F(1,25 = 4.74$, $p<0.05$]. This is explained by a higher percentage of intrusions from a previous list, when the load on control processes is higher (HI) compared to when the load on control processes is lower (i.e. LI).

RECALL is a significant main effect [$F(1,37) = 37.49$, $p<0.001$]. A polynomial contrast confirms that this factor is better accounted for by a quadratic[63] increase [F(1,25) = 19.66; p<.0.001]: as illustrated in Figure 3.18, increasingly more previous list intrusions are produced at the increase of the load on the memory system.

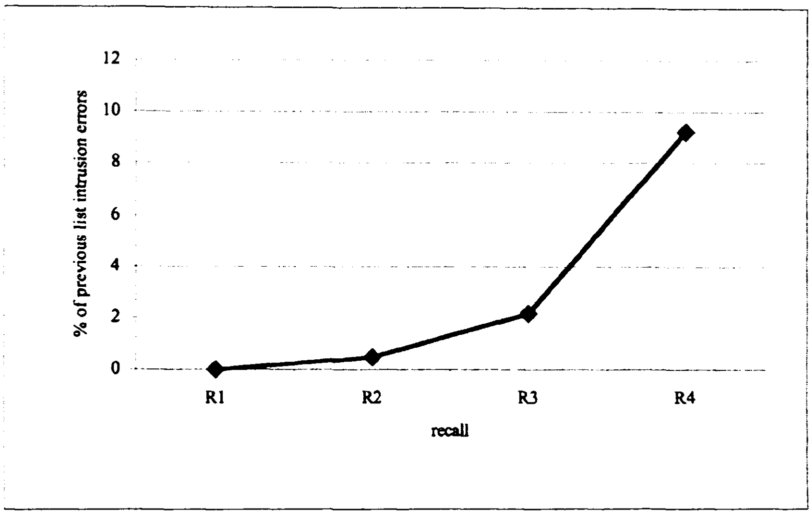

Figure 3. 18: Updating task - Previous list intrusion errors - (YA and AE) - main effect of RECALL

The main effect of STIMULUS is also significant [F(1,25) = 32.07, p<0.001], due to a higher percentage of intrusions from a previous list errors being produced with numbers than with words.

The main effect of GROUP is not significant[64].

The interaction RECALL X STIMULUS is significant [F(1,35) = 16.00, p<0.001[65]. In order to analyse it further, a Paired Samples t-test was conducted for each level of RECALL, comparing the performance at the different levels of STIMULUS (noun and number). Figure 3.19 illustrates that the difference between the two levels of STIMULUS is only significant in the condition of

[63] A linear increase was also found to be significant [F(1,25) = 55.77; p<.0.001].

[64] [F(1,25) = 1.36, p>0.05]

[65] The other interactions were not significant (INHIBITION X GROUP [F(1,25) = 0.00, p>0.05]; RECALL X GROUP [F(1,37) = 2.95, p>0.05], STIMULUS X GROUP [F(1,25) = 1.57, p>0.05], INHIBITION X RECALL [F(2,47) = 2.51, p>0.05], INHIBITION X RECALL X GROUP [F(2,47) = 1.18, p>0.05], INHIBITION X STIMULUS [F(1,25) = 0.01, p>0.05], INHIBITION X STIMULUS X GROUP [F(1,25) = 0.00, p>0.05];, RECALL X STIMULUS X GROUP [F(1,35) = 3.61, p>0.05]; INHIBITION X RECALL X STIMULUS [F(2,52) = 2.04, p>0.05]; and INHIBITION X RECALL X STIMULUS X GROUP [F2,52) = 2.36, p>0.05]).

highest load on the memory system (R4 [t(26)= -4.86 p<0.005]), but it is not significant in the conditions of lower load on maintenance[66].

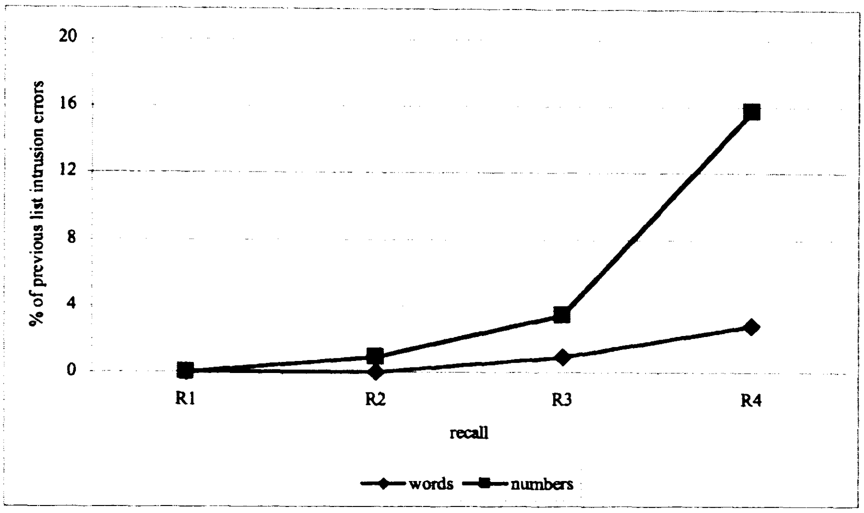

Figure 3. 19: Updating task - Previous list intrusion errors - (YA and AE) - interaction RECALL X STIMULUS

ADULTS AND ELDERLY WITH LOWER EDUCATION

Another 2X2X4X2 mixed design ANOVA was conducted in order to investigate the differences in the production of intrusion errors of items from a previous list between the other two groups (elderly and adults matched for education), across conditions.

The between-subjects independent variable was GROUP with two levels (A and E). The within-subjects factors and the dependent variable were the same as in the previous analysis.

The analysis revealed a significant main effect of INHIBITION [F(1,23) = 5.88, p<0.05] that is explained by a higher percentage of intrusions from a previous list when the load on control processes i higher (HI) compared to when the load on control processes is lower (LI).

[66]R1 [n.s.: Could not compute the difference since all scores were equivalent], R2 [t(26)= -1.36, p>0.05]), R3 [t(26)= -2.13, p>0.05]

The main effect of RECALL is significant [$F(2,39) = 57.35$, $p<0.001$]. A polynomial contrast confirms that this factor is better accounted for by a quadratic[67] increase [$F(1,23) = 44.59$; $p<.0.001$]. Figure 3.20 shows that increasingly more previous list intrusions are produced at the increase of the load on the memory system.

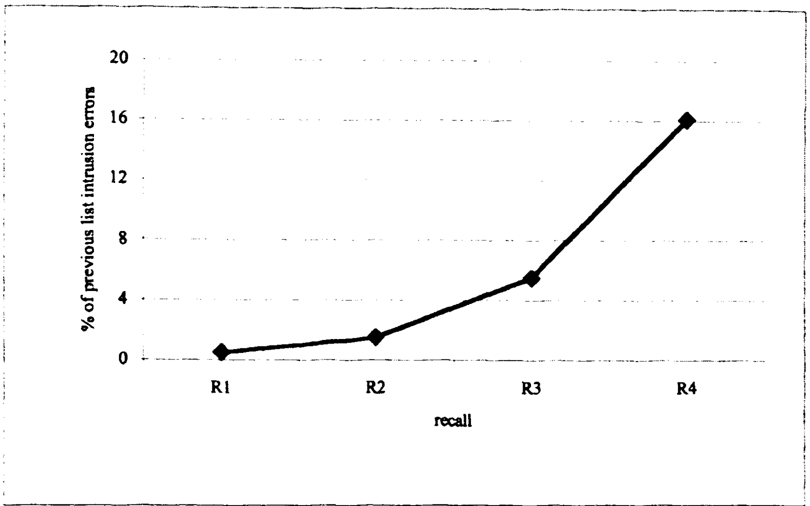

Figure 3. 20: Updating task - Previous list intrusion errors - (A and E) - main effect of RECALL

The main effect of STIMULUS is significant [$F(1,23) = 43.68$, $p<0.001$], due to a higher percentage of intrusions from a previous list errors being produced with numbers than with words.

No significant main effect of GROUP [$F(1,23) = 4.00$, $p>0.05$] was found.

The interaction INHIBITION X RECALL is significant [$F(3,69) = 3.10$, $p<0.05$]. This was investigated with a Paired Samples t-test, comparing the performance on the different levels of INHIBITION (low and high). As illustrated in Figure 3.21, the difference between LI and HI is only significant when the task requires to recall two items (R2 [$t(24)= -2.75$, $p<.05$]), or three

[67] A linear increase was also found to be significant [$F(1,23) = 77.50$; $p<.0.001$].

items (R3 [t(24)= -3.99, p <0.01]) but not when the items to recall are one or four[68].

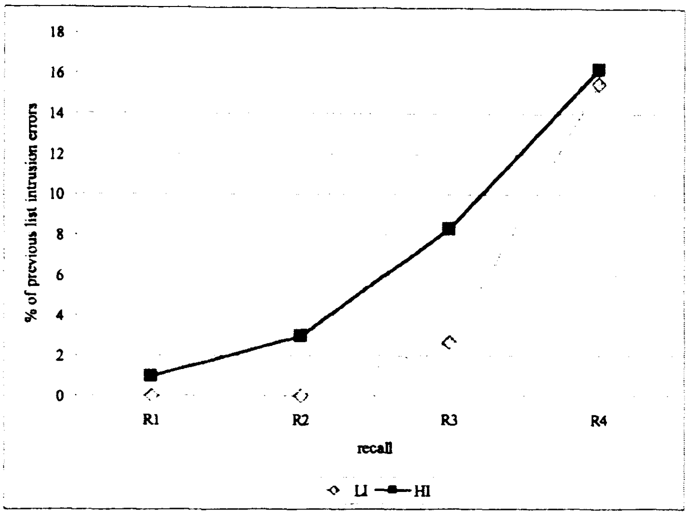

Figure 3. 21: Updating task - Previous list intrusion errors - (A and E) - interaction INHIBITION X RECALL

The interaction RECALL X STIMULUS is significant[F(2,39) = 40.42, p <0.001]. In order to investigate this interaction, a Paired Samples t-test was conducted for each level of RECALL, comparing the performance at the different levels of STIMULUS. As Figure 3.22 illustrates, the difference between nouns and numbers is only significant in the condition with two items to recall (R2 [t(24)= -2.75, p<0.05]) and with four items to recall (R4 [t(24)= -8.35, p<0.005]), but it is not significant in the other two conditions[69].

[68] R1 [t(24)= -1.00, p>0.05]; R4 [t(24)= 0.00, p>0.05]

[69] R1 [t(24) = -1.00; p>0.05], R3 [t(24)= -1.43, p>0.05]

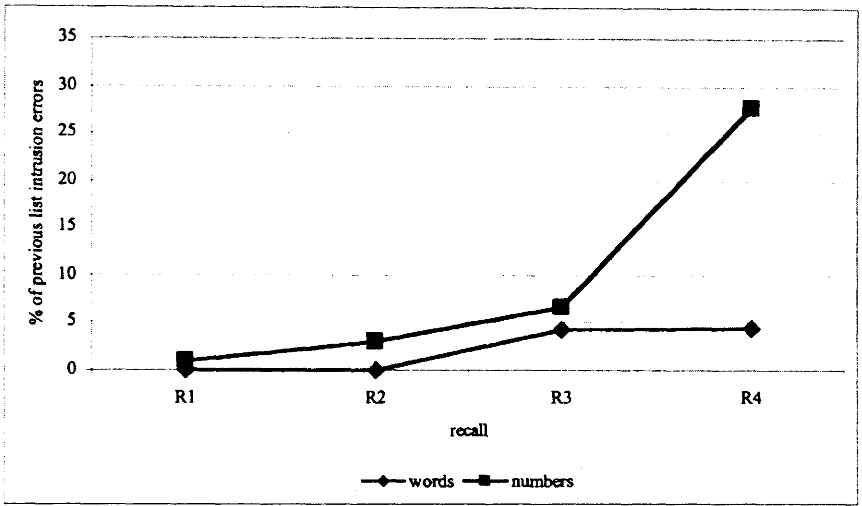

Figure 3. 22: Updating task - Previous list intrusion errors - (A and E) - interaction RECALL X STIMULUS

Moreover, inhibition, recall and stimulus interact with one another, as the INHIBITION X RECALL X STIMULUS interaction is significant [$F(2,43) = 5.16$, $p<0.02$][70]. This was investigated performing separate Paired Sample t-test analysis for the task recalling words and the task recalling numbers, comparing the performance at the different levels of INHIBITION (low and high) for each level of RECALL. As illustrated in Figure 3.23, this shows that with words the difference between LI and HI is not significant at any of the levels of RECALL[71]. With numbers, the difference between LI and HI is only significant when the task requires to recall three items (R3 [$t(24)= -2.75$, $p<.05$), but not at any other condition of recall[72].

[70] The other interactions were not significant (INHIBITION X GROUP [$F(1,23) = 2.10$, $p>0.05$], RECALL X GROUP [$F(2,39) = 2.83$, $p>0.05$], STIMULUS X GROUP [$F(1,23) = 0.40$, $p>0.05$], INHIBITION X RECALL X GROUP [$F(3,69) = 1.59$, $p>0.05$], INHIBITION X STIMULUS [$F(1,23) = 0.25$, $p>0.05$], INHIBITION X STIMULUS X GROUP [$F(1,23) = 0.25$, $p>0.05$]; RECALL X STIMULUS X GROUP [$F(2,39) = 0.61$, $p>0.05$]., and INHIBITION X RECALL X STIMULUS X GROUP [$F(2,43) = 1.57$, $p>0.05$]).

[71] R1 [n.s.: Could not compute the difference since all scores were equivalent]; R2 [n.s.: Could not compute the difference since all scores were equivalent]; R3 [$t(24)= -1.73$, $p>0.05$]); R4 [$t(24)= -2.62$, $p>0.05$].

[72] R1 [$t(24)= -1.00$, $p>0.05$]; R2[$t(24)= -2.75$, $p>0.05$]; R4 [$t(24)= 1.13$, $p>0.05$].

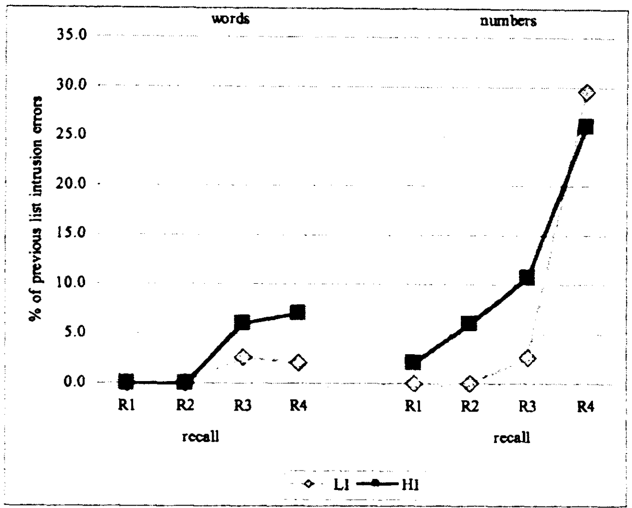

Figure 3. 23: Updating task - Previous list intrusion errors - (A and E) - interaction INHIBITION X RECALL X STIMULUS

3.3.2.4. Invention errors

YOUNG ADULTS AND ADULTS WITH HIGHER EDUCATION

A 2x2x4x2 mixed design ANOVA was conducted to see differences in the production of invention errors between the group of young adults (YA) and the group of adults (AE) matched for education, across conditions.

The within-subjects independent variables were the same as in the previous analyses. The dependent variable was the percentage of inventions produced (as a proportion of the total number of responses).

The analysis revealed a significant main effect of RECALL [$F(2,51) = 10.14$, $p<0.001$]. A polynomial contrast confirms that this factor is only accounted for by a linear increase [$F(1,25) = 29.82$; $p<.0.001$], with increasingly more inventions being produced with more items to be recalled. No other significant trends were observed. Figure 3.24 illustrates the trend.

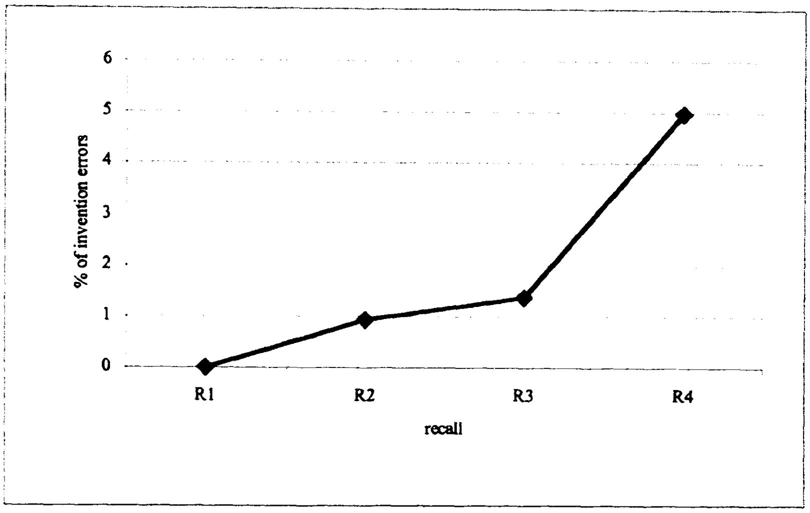

Figure 3. 24: Updating task - Invention errors - (YA and AE) - main effect of RECALL

A significant main effect of STIMULUS was also found [$F(1,25) = 27.06$, $p<0.001$], due to a higher percentage of invention errors being produced with numbers than with words.

The main effect of GROUP[73] and INHIBITION [74]are not significant.

A significant interaction was also found for RECALL X STIMULUS [$F(1,35) = 16.00$, $p<0.001$][75]. In order to analyse it, a Paired Samples t-test was conducted for each level of RECALL, comparing the performance at the different levels of STIMULUS (noun and number). As illustrated in Figure 3.25, this shows that the difference between nouns and numbers is only significant in the

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[73] [$F(1,25) = 1.33$, $p>0.05$]
[74] [F(1,25 = 1.91, $p>0.05$]
[75] The other interactions were not significant (INHIBITION X GROUP [$F(1,25) = 0.87$, $p>0.05$]; RECALL X GROUP [$F(2,51) = 0.12$, $p>0.05$], STIMULUS X GROUP [$F(1,25) = 0.43$, $p>0.05$], INHIBITION X RECALL [$F(2,57) = 1.21$, $p>0.05$], INHIBITION X RECALL X GROUP [$F(2,57) = 1.85$, $p>0.05$], INHIBITION X STIMULUS [$F(1,25) = 0.58$, $p>0.05$], INHIBITION X STIMULUS X GROUP [$F(1,25) = 2.94$, $p>0.05$];, RECALL X STIMULUS X GROUP [$F(2,59) = 1.02$, $p>0.05$]; INHIBITION X RECALL X STIMULUS [$F(2,56) = 0.81$, $p>0.05$]; and INHIBITION X RECALL X STIMULUS X GROUP [F2,56) = 1.96, $p>0.05$]).

condition of highest load on the memory system (R4 [t(26)= -4.89 p<0.005]), but it is not significant in the conditions of lower load on maintenance[76].

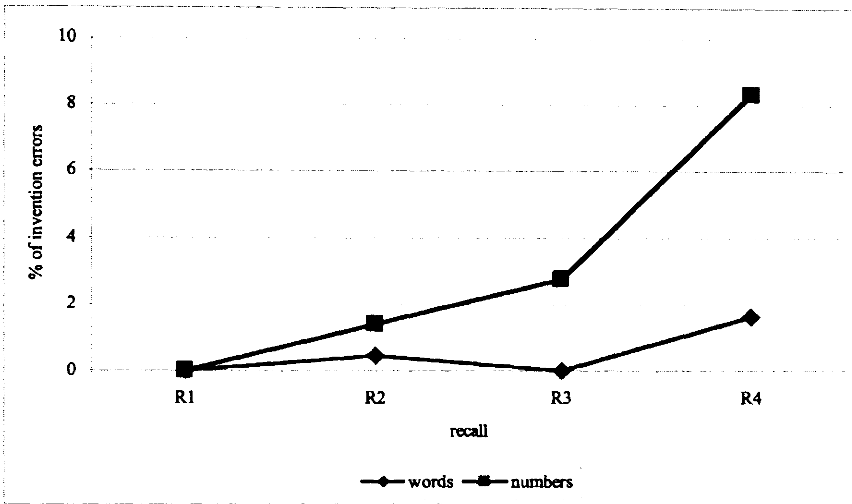

Figure 3. 25: Updating task - Invention errors - (YA and AE) - interaction RECALL X STIMULUS

ADULTS AND ELDERLY WITH LOWER EDUCATION

Another 2X2X4X2 mixed design ANOVA with mixed design was performed in order to investigate the differences in the production of invention errors between the groups of elderly (E) and the group of adults (A) matched for education, across conditions.

The within-subjects factors and the dependent variable were the same as in the previous analysis.

The main effect of GROUP is significant [F(1,23) = 7.04, p<0.02] and explained by a higher production of inventions in the elderly group compared to the adult group.

The analyses also revealed a significant main effect of RECALL [F(3,69) = 6.15, p<0.002]. A polynomial contrast confirms that the factor is only

[76] R1 [n.s.: Could not compute the difference since all scores were equivalent], R2 [t(26)= -1.00, p>0.05]), R3 [t(26)= -2.55, p>0.05].

accounted for by a linear increase [F(1,23) = 24.03; p<.0.001], with the percentage of inventions increasing proportionally to the increase n the number of items to be recalled. No other significant trends were observed, as illustrated in Figure 3.26.

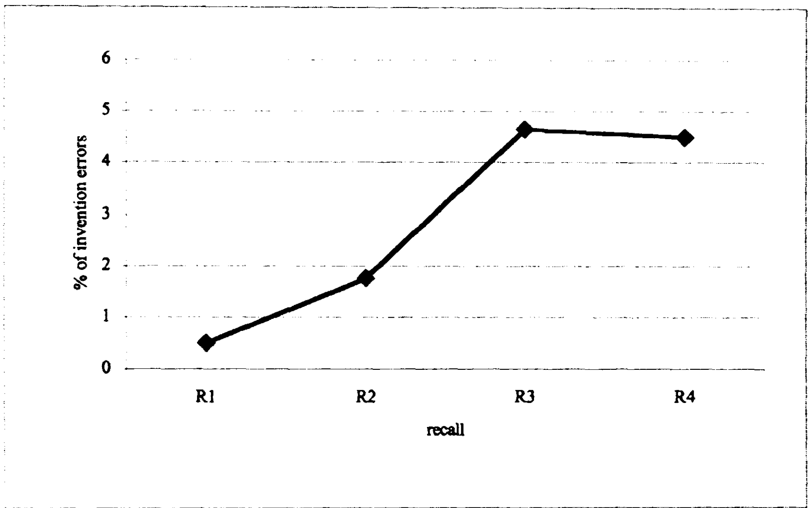

Figure 3. 26: Updating task - Invention errors - (A and E) - main effect of RECALL

STIMULUS is a significant main effect [F(1,23) = 20.93, p<0.001], due to a higher percentage of invention errors being produced with numbers than with words.

The interactions STIMULUS X GROUP is significant [F(1,23) = 6.82, p<0.02]. A between-subjects ANOVA was performed for each level of STIMULUS, in order to investigate the interaction. The independent variable was GROUP with two levels (A and E) and the dependent variable was the percentage of inventions produced when recalling words and when recalling numbers. As illustrated in Figure 3.27, the production of invention errors is significantly worse in the elderly group only when the task requires to recall numbers [F(1,23) = 8.43; p<0.01], but not when it requires to recall words[77].

[77] [F(1,23) = 0.31; p>0.05].

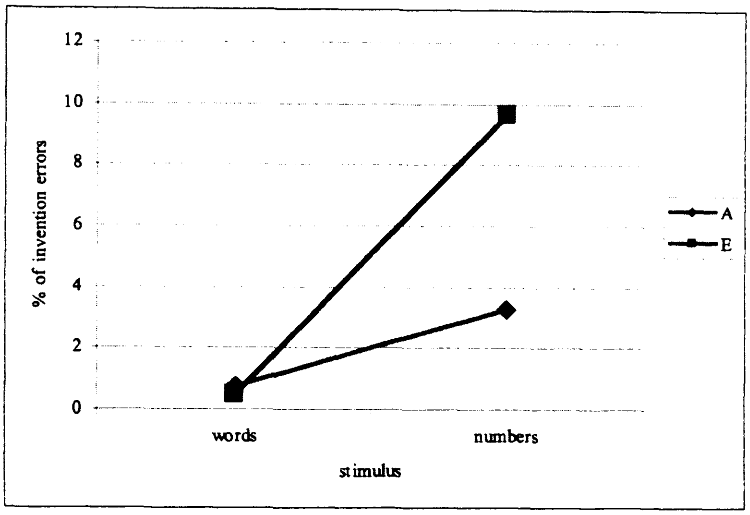

Figure 3. 27: Updating task - Invention errors - (A and E) - interaction STIMULUS X GROUP

INHIBITION X RECALL is a significant interaction [$F(3,69) = 3.37$, $p<0.05$]. It was investigated by conducting a Paired Samples t-test for each level of RECALL, comparing the performance on the different levels of INHIBITION (low and high). Figure 3.28 shows that the difference between low and high inhibition is only significant when the task requires to recall three items (R3 [$t(24)= 3.06$, $p<.05$]), but not in the other conditions of recall[78].

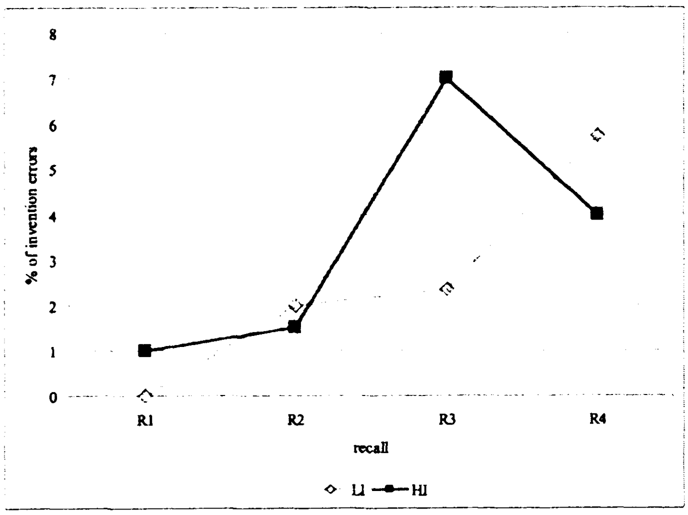

Figure 3. 28: Updating task - Invention errors - (A and E) - interaction INHIBITION X RECALL

[78] R1 [$t(24)= -1.00$, $p>0.05$]), R2 [$t(24)= 0.57$, $p>0.05$], and R4 [$t(24)= 1.02$, $p>0.05$]

Inhibition and recall also interact with group: INHIBITION X RECALL X GROUP is a significant interaction [$F(3,69) = 3.21$, $p<0.05$]. The same Paired Sample t-test was performed separately in the two groups in order to investigate the interaction. The results, illustrated in Figure 3.29, show that only in the elderly group the difference between conditions of low and high load on control processes is significant when the task required to recall three items (R3 [$t(14)= -3.06$, $p<.05$])[79]. In the group of adults there is no difference in the production of invention errors between conditions of inhibition, at any of the levels of recall[80].

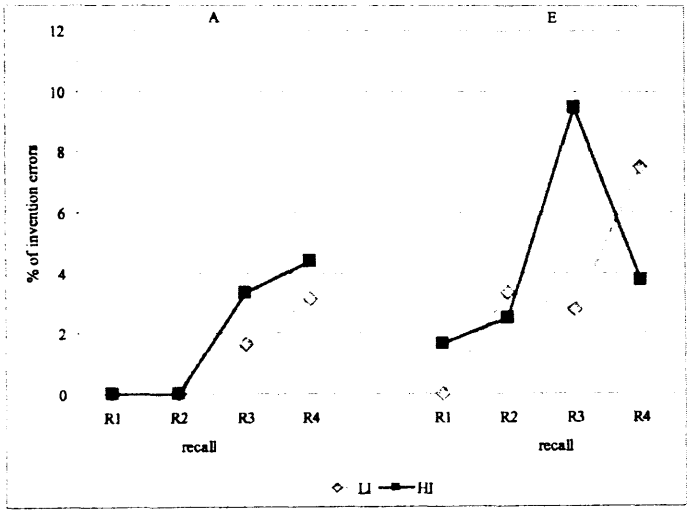

Figure 3. 29: Updating task - Invention errors - (A and E) - interaction INHIBITION X RECALL X GROUP

RECALL X STIMULUS is also a significant interaction [$F(3,69) = 3.62$, $p <0.02$]. A Paired Samples t-test was conducted for each level of RECALL, comparing the performance at the different levels of STIMULUS. This shows that the difference between nouns and numbers is only significant in the

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[79] and not in the other conditions of recall (R1 [$t(14)= -1.00$, $p>0.05$]; R2 [$t(14)= 0.56$, $p>0.05$]; R4 [$t(14)= 1.50$, $p>0.05$])

[80] R1[n.s.: Could not compute the difference since all scores were equivalent]; R2 [n.s.: Could not compute the difference since all scores were equivalent]; R3 [$t(9)= -1.00$, $p>0.05$]; R4 [$t(9)= -0.69$, $p>0.05$]

conditions with higher load on maintenance (R3 [t(24)= -3.36, p<0.02]) and R4 [t(24)= -5.04, p<0.005]), and it is not significant in the other two conditions[81], as illustrated in Figure 3.30.

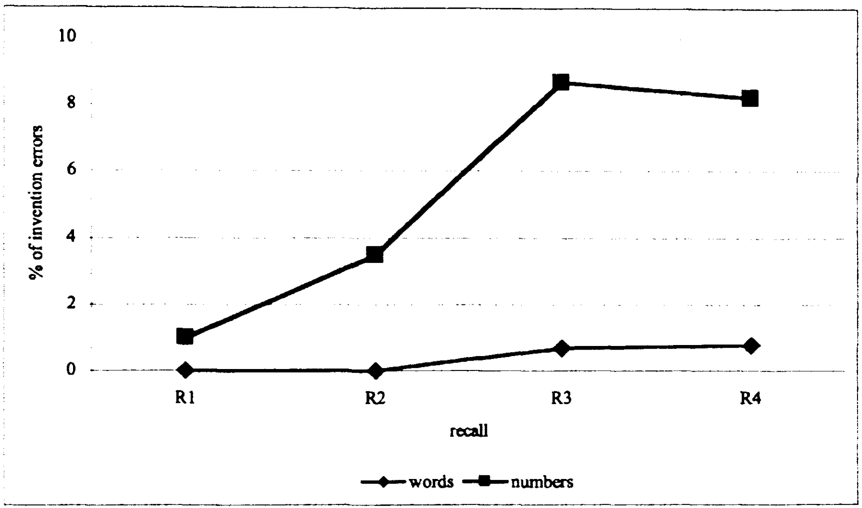

Figure 3. 30: Updating task - Invention errors - (A and E) - interaction RECALL X STIMULUS

Recall and stimulus also interact with inhibition: the interaction INHIBITION X RECALL X STIMULUS is significant [F(3,69) = 5.63, p<0.005][82]. This was further investigated by conducting separate Paired Sample t-test analysis for the condition with low and the condition with high inhibition demand, comparing the performance on the different levels of STIMULUS at each level of RECALL. Figure 3.31 illustrates that when the load on control processes is lower (LI) the difference between production of invention errors with words and with numbers is only significant when the load on maintenance is very high (R4 [t(24)= -4.24, p<0.01][83]. When the load on control processes is higher

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[81] R1 [t(24) = -1.00; p>0.05], R2 [t(24)= -1.90, p>0.05]

[82] The other interactions were not significant (INHIBITION X GROUP [F(1,23) = 0.00, p>0.05], RECALL X GROUP [F(2,39) = 0.57, p>0.05], INHIBITION X STIMULUS [F(1,23) = 2.86, p>0.05], INHIBITION X STIMULUS X GROUP [F(1,23) = 0.17, p>0.05]; RECALL X STIMULUS X GROUP [F(2,39) = 0.60, p>0.05]., and INHIBITION X RECALL X STIMULUS X GROUP [F(2,43) = 1.60, p>0.05]).

[83] and not significant at any of the other levels of RECALL (R1 [n.s.: Could not compute the difference since all scores were equivalent]; R2 [t(24)= -2.14, p>0.05]; R3 [t(24)= -0.83, p>0.05])

(HI) the difference between production of invention errors with words and with numbers is only significant when the task requires to recall three items (R3 [t(24)= -4.45, p<0.01])[84].

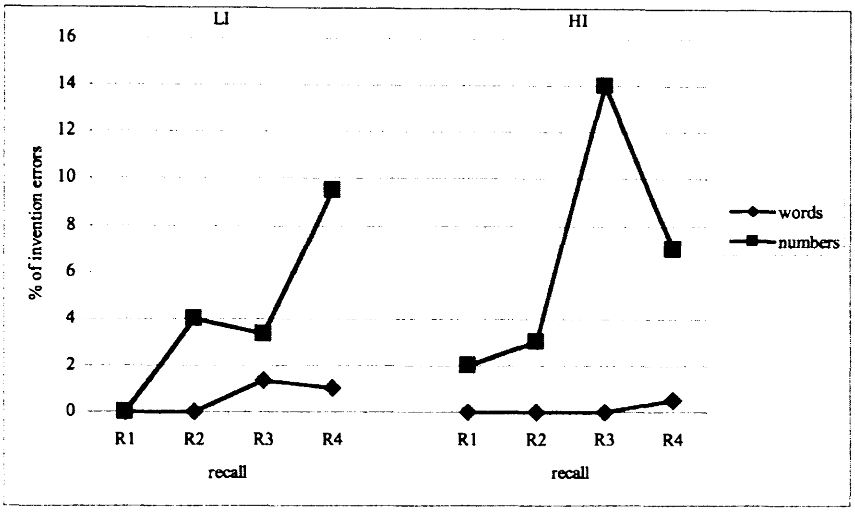

Figure 3. 31: Updating task - Invention errors - (A and E) - interaction INHIBITION X RECALL X STIMULUS

3.3.2.5. Omission errors

YOUNG ADULTS AND ADULTS WITH HIGHER EDUCATION

A 2x2x4x2 mixed design ANOVA was conducted to see differences in the production of omission errors between the group of young adults (YA) and the group of adults (AE) matched for education, across conditions.

The within-subjects independent variables were the same as in the previous analyses, and the dependent variable was the percentage of omissions produced (as a proportion of the total number of responses).

The analyses revealed a significant main effect of GROUP [F(1,25) = 7.48, p <0.02], with the group of adults producing more omissions than the group of younger adults

[84] and not significant at any of the other levels of RECALL (R1 [t(24)= -1.00, p>0.05]; R2 [t(24)= -1.37, p>0.05]; R4 [t(24)= -2.70, p>0.05])

INHIBITION is also a significant main effect [$F(1,25 = 11.56$, $p<0.005$], explained by more omission errors being produced when the load on control processes is higher (HI) compared to when the load on control processes is lower (LI).

A significant main effect of RECALL was found [$F(3,75) = 2.54$, $p<0.001$], and better accounted for by a quadratic[85] increase [$F(1,25) = 36.98$; $p<.0.001$], with increasingly more omissions being produced with the increase of load on maintenance. This trend was investigated further by comparing with a Paired Samples t-test each level of recall with the following. The results, illustrated in Figure 3.32 show that there is no difference in the production of omission errors between the condition where to recall one item (R1) and the condition where to recall two items (R2)[86], nor between the condition where to recall two items (R2) and the condition where to recall three items (R3)[87]. The condition where participants were asked to recall four items (R4), instead, leads participants to produce significantly more omissions than the condition where they are asked to recall three items (R3) [$t(26) = -5.97$; $p<0.005$].

[85] A linear increase was also found to be significant [$F(1,25) = 27.95$; $p<.0.001$].
[86] [n.s.: Could not compute the difference since all scores were equivalent]
[87] [$t(26) = -1.93$; $p>0.05$]

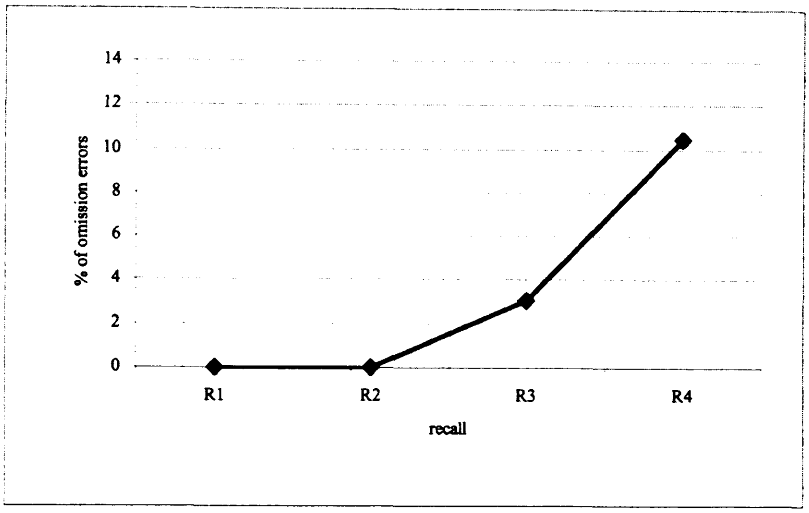

Figure 3. 32: Updating task - Omission errors - (YA and AE) - main effect of RECALL

The main effect of STIMULUS is significant [F(1,25) = 7.30, p<0.02], due to more omissions being produced by participants when recalling numbers compared to when recalling words.

The interactions INHIBITION X GROUP is significant [F(1,25) = 5.38, p<0.05], and it was further investigated by conducting a between-subjects ANOVA for each level of INHIBITION. The independent variable was GROUP with two levels (YA and AE) and the dependent variable was the percentage of omissions produced in the condition of low load on control processes (LI) and in the condition of high load on control processes (HI). As illustrated in Figure 3.33, the production of omission errors is significantly worse in the group of adults only when the task poses high demands on the inhibitory processes [F(1,25) = 9.75; p<0.005], but not when this demand is lower[88].

[88] [F(1,25) = 3.64; p>0.05]

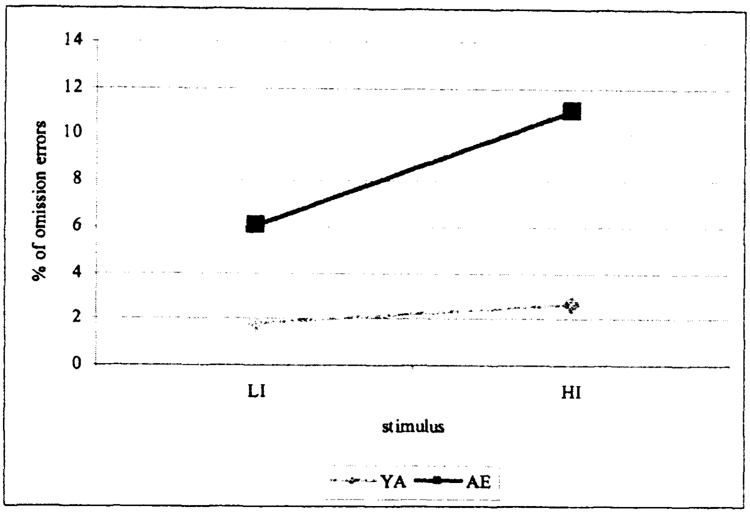

Figure 3. 33: Updating task - Omission errors - (YA and AE) - interaction INHIBITION X GROUP

RECALL X GROUP is a significant interaction [$F(3,75) = 6.93$, $p<0.001$]. A between-subjects ANOVA was performed for each level of RECALL, in order to investigate the interaction. The independent variable was again GROUP with two levels (YA and AE) and the dependent variable was the percentage of omissions produced at each level of RECALL (R1, R2, R3 and R4). As shown in Figure 3.34, the production of omission errors is significantly worse in the adult group only when the load on the memory system is higher (R3 [$F(1,25) = 4.36$; $p<0.05$], R4 [$F(1,25) = 9.02$; $p<0.01$]) but not when the load on the memory system is lower[89].

[89] R1, R2 [n.s.: Could not compute the difference since all scores were equivalent].

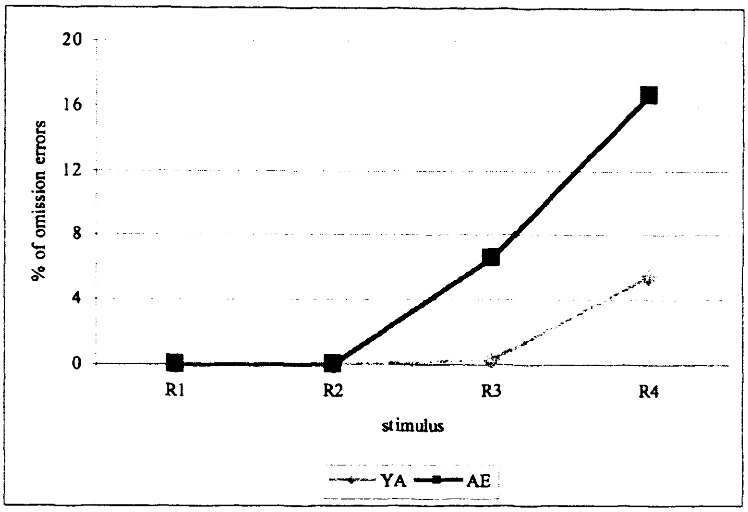

Figure 3. 34: Updating task - Omission errors - (YA and AE) - interaction RECALL X GROUP

The interaction RECALL X STIMULUS is significant [$F(3,75) = 8.03$, $p<0.001$], and it was investigated by conducting a Paired Samples t-test for each level of RECALL, comparing the performance at the different levels of STIMULUS. This shows, as illustrated in Figure 3.35, that the difference between nouns and numbers is only significant in the condition of highest load (R4 [$t(26)= -3.31$; $p<0.02$]), but it is not significant in the conditions of lower load on the memory system[90].

[90] R1 [n.s.: Could not compute the difference since all scores were equivalent], R2 [n.s.: Could not compute the difference since all scores were equivalent]), R3 [$t(26)= -0.00$, $p>0.05$]

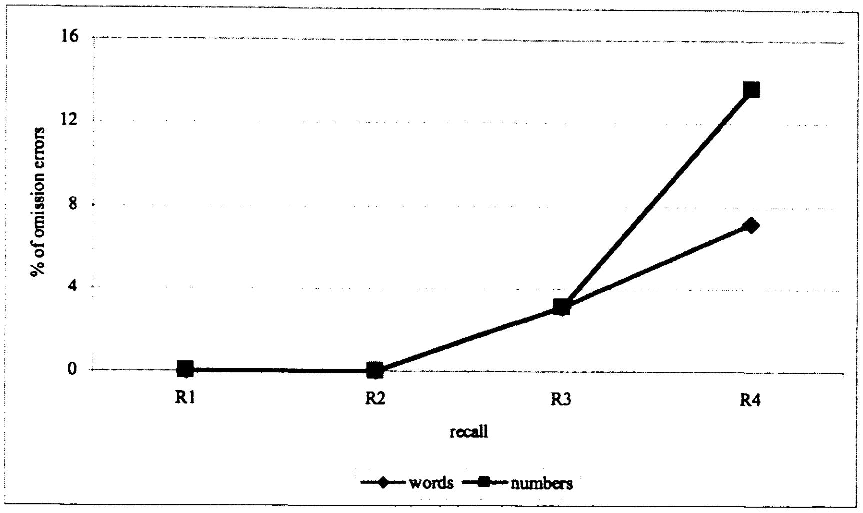

Figure 3. 35: Updating task - Omission errors - (YA and AE) - interaction RECALL X STIMULUS

Recall and stimulus also interact with group: the RECALL X STIMULUS X GROUP interaction is significant [$F(3,75) = 3.15$, $p<0.05$][91]. The same Paired Samples t-test used in the previous analysis was conducted separately in the two. As illustrated in Figure 3.36, the results show that in the group of adults there is a significant difference in the production of omissions when recalling words compared to when recalling numbers only when the items to recall are four (R4 [$t(11)= -3.26$; $p<0.05$])[92]. In the group of younger adults, no difference was found in the production of omissions with words and numbers at any of the levels of recall[93].

[91] The other interactions were not significant (STIMULUS X GROUP [$F(1,25) = 1.84$, $p>0.05$], INHIBITION X RECALL [$F(3,75) = 2.54$, $p>0.05$], INHIBITION X RECALL X GROUP [$F(3,75) = 1.65$, $p>0.05$], INHIBITION X STIMULUS [$F(1,25) = 0.02$, $p>0.05$], INHIBITION X STIMULUS X GROUP [$F(1,25) = 0.25$, $p>0.05$]; INHIBITION X RECALL X STIMULUS [$F(3,75) = 0.05$, $p>0.05$]; and INHIBITION X RECALL X STIMULUS X GROUP [$F(3,75) = 2.37$, $p>0.05$]).

[92] No significant difference was found in the other conditions (R1, R2 [n.s.: Could not compute the difference since all scores were equivalent]; R3 [$t(26)= 0.19$, $p>0.05$])

[93] R1, R2 [n.s.: Could not compute the difference since all scores were equivalent]; R3 [$t(26)= -1.00$, $p>0.05$]; R4 [$t(26)= -1.57$, $p>0.05$].

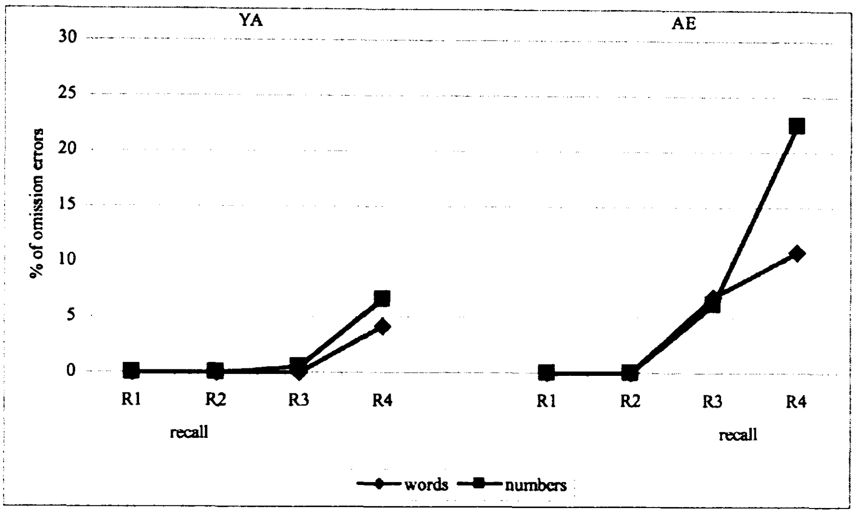

Figure 3. 36: Updating task - Omission errors - (YA and AE) - interaction RECALL X STIMULUS X GROUP

ADULTS AND ELDERLY WITH LOWER EDUCATION

Another 2X2X4X2 mixed design ANOVA was performed in order to investigate the differences in the production of omission errors between the group of elderly (E) and the group of adults (A), across conditions.

The within-subjects factors and the dependent variable were the same as in the previous analysis.

The analysis revealed a significant main effects of GROUP [$F(1,23) = 12.78$, $p<0.005$], explained by a higher production of omissions in the elderly group compared to the adult group.

The main effect of INHIBITION is significant [$F(1,23) = 49.63$, $p<0.001$], due to a higher percentage of omissions when the load on control processes is higher (i.e. HI), compared to when the load on control processes is lower (i.e. LI).

RECALL is also a significant main effect [$F(2,43) = 29.96$, $p<0.001$][94]. A polynomial contrast confirms that this factor is better accounted for by a

[94] The main effect of STIMULUS was not significant [$F(1,23) = 0.66$, $p>0.05$].

quadratic[95] increase [F(1,23) = 15.07; p<.0.002], as shown in Figure 3.37, with increasingly more omissions being produced with the increase of load on maintenance.

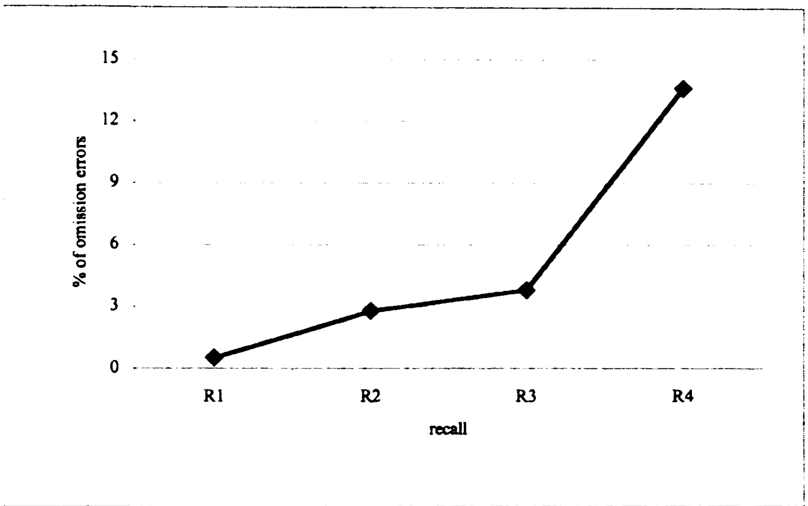

Figure 3. 37: Updating task - Omission errors - (A and E) - main effect of RECALL

The interaction INHIBITION X GROUP is significant [F(1,23) = 10.25, p<0.005]. A between-subjects ANOVA was performed at each level of INHIBITION, in order to investigate the interaction. The independent variable was GROUP with two levels (A and E) and the dependent variable was the percentage of omissions produced in the condition of low load on control processes (LI) and in the condition of high load on control processes (HI). This is illustrated in Figure 3.38, showing that the production of omission errors is significantly worse in the group of elderly only when the task poses high demands on the inhibitory processes [F(1,23) = 12.99; p<0.002], but not when this demand is lower[96].

[95] A linear [F(1,23) = 59.63; p<.0.001] and cubic increase[F(1,23) = 4.41; p<.0.05] were also found to be significant.
[96] [F(1,23) = 3.99; p>0.05].

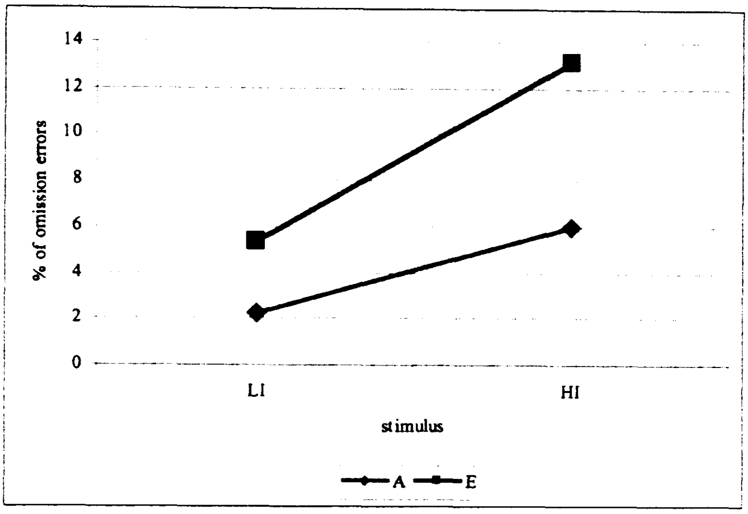

Figure 3. 38: Updating task - Omission errors - (A and E) - interaction INHIBITION X GROUP

Inhibition also interacts with recall: the INHIBITION X RECALL interaction is significant [F(2,44) = 4.18, p<0.05][97]. In order to investigate this interaction, a Paired Samples t-test was conducted for each level of RECALL, comparing performance at the different levels of INHIBITION (low and high). This shows that the difference in production of omissions between LI and HI is only significant when the task requires to recall two items (R2 [t(24)= -2.86, p<.05]), or four items (R4 [t(24)= -3.61, p<0.02])[98], as illustrated in Figure 3.39.

[97] The other interactions were not significant (RECALL X GROUP [F(2,43) = 1.90, p>0.05],STIMULUS X GROUP [F(1,23) = 0.26, p>0.05], INHIBITION X RECALL X GROUP [F(2,44) = 0.81, p>0.05], INHIBITION X STIMULUS [F(1,23) = 0.09, p>0.05], INHIBITION X STIMULUS X GROUP [F(1,23) = 0.13, p>0.05]; RECALL X STIMULUS [F(3,69) = 0.11, p>0.05], RECALL X STIMULUS X GROUP [F(3,69) = 1.79, p>0.05]., INHIBITION X RECALL X STIMULUS [F(2,43) = 1.21, p>0.05], and INHIBITION X RECALL X STIMULUS X GROUP [F(2,43) = 0.16, p>0.05]).

[98] And it was not significant in the other conditions of recall (R1 [t(24)= -1.00, p>0.05]), R3 [t(24)= -2.06, p>0.05])

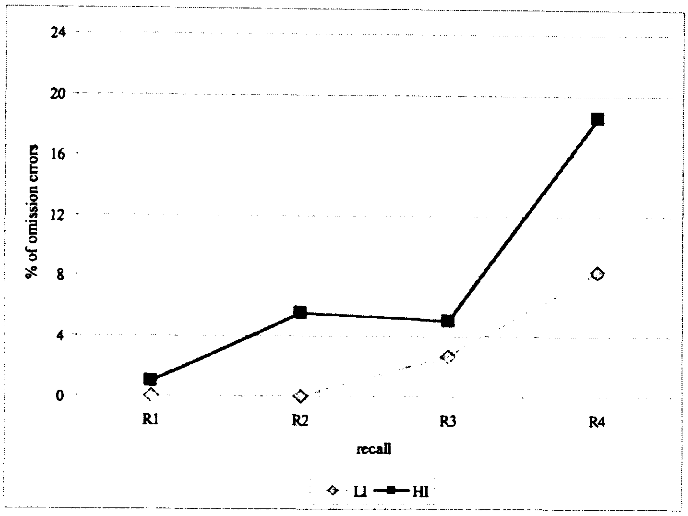

Figure 3. 39: Updating task - Omission errors - (A and E) - interaction INHIBITION X RECALL

3.3.2.6. Summary of Updating Results

The differences between groups will be reported in this summary, as this was the main aim of the chapter. Table 3.2 illustrates a summary of the effects of ageing on the Updating task. Recall performance is significantly worse in the group of elderly (E) compared with the group of adults (A), and in the group of educated adults (AE) compared to the group of young adults (YA). AE also produce more same list intrusion errors compared to YA. However, this difference is only significant when more items have to be inhibited. Moreover, the difference between the groups is only present when recalling three or four words, while no difference is found between groups when recalling numbers.

Group E produced more inventions than group A, but only when recalling numbers. Moreover, group E produced more inventions when having to recall three items whilst inhibiting a high number of irrelevant items. No such difference was found in group A.

Group E omitted more items than group A, and group AE more than group YA. In both cases this is only significant at the high level of inhibition.

Moreover, AE only produced more omissions than YA when having to recall three or four items. When recalling four items, AE omit more numbers than nouns. This difference was not found in YA.

Table 3. 2: Effects of age on WM -Updating task - Effects of group - summary of results

		RESULTS	
		YA&AE (high education)	A&E (low education)
RECALL	GROUP	YA>AE	A>E
	INHIBITION X GROUP	n.s.	n.s.
	RECALL X GROUP	n.s.	n.s.
	STIMULUS X GROUP	n.s.	n.s.
	INHIB X REC X GROUP	n.s.	n.s.
	INHIB X STIM X GROUP	n.s.	n.s.
	REC X STIM X GROUP	n.s.	n.s.
	INHIB X REC X STIM X GROUP	n.s.	n.s.
SAME LIST INTRUSIONS	GROUP	YA>AE	n.s.
	INHIBITION X GROUP	YA>AE with HI	n.s.
	RECALL X GROUP	n.s.	n.s.
	STIMULUS X GROUP	n.s.	n.s.
	INHIB X REC X GROUP	n.s.	n.s.
	INHIB X STIM X GROUP	n.s.	n.s.
	REC X STIM X GROUP	With W: YA>AE only with R3; R4 With N: YA=AE	n.s.
	INHIB X REC X STIM X GROUP	n.s.	n.s.
PREVIOUS LIST INTRUSIONS	GROUP	n.s.	n.s.
	INHIBITION X GROUP	n.s.	n.s.
	RECALL X GROUP	n.s.	n.s.
	STIMULUS X GROUP	n.s.	n.s.
	INHIB X REC X GROUP	n.s.	n.s.
	INHIB X STIM X GROUP	n.s.	n.s.
	REC X STIM X GROUP	n.s.	n.s.
	INHIB X REC X STIM X GROUP	n.s.	n.s.
INVENTIONS	GROUP	n.s.	A>E
	INHIBITION X GROUP	n.s.	n.s.
	RECALL X GROUP	n.s.	n.s.
	STIMULUS X GROUP	n.s.	A>E with N
	INHIB X REC X GROUP	n.s.	In A: LI=HI In E: LI>HI with R3
	INHIB X STIM X GROUP	n.s.	n.s.
	REC X STIM X GROUP	n.s.	n.s.
	INHIB X REC X STIM X GROUP	n.s.	n.s.

		RESULTS	
		YA&AE (high education)	A&E (low education)
OMISSIONS	GROUP	YA>AE	A>E
	INHIBITION X GROUP	YA>AE with HI	A>E with HI
	RECALL X GROUP	YA>AE with R3; R4	n.s.
	STIMULUS X GROUP	n.s.	n.s.
	INHIB X REC X GROUP	n.s.	n.s.
	INHIB X STIM X GROUP	n.s.	n.s.
	REC X STIM X GROUP	In YA: W=N In AE: W>N with R4	n.s.
	INHIB X REC X STIM X GROUP	n.s.	n.s.

Key: YA=Young adults (high education); AE=Adults (high education); A=Adults (low education); E=Elderly (low education); LI=Low Inhibition; HI=High Inhibition; R1, R2, R3, R4=1 item to recall, 2 items to recall etc.; W=Words (i.e. nouns); N=Numbers; > = better performance (i.e. more items recalled or fewer errors); < = worse performance (i.e. fewer items recalled or more errors); n.s. = not significant;

3.4. Discussion

The aim of this study was to further investigate the processes studied in the previous chapter, but especially the effects of age and education on performance on various span tests and in the updating task.

It was hypothesised that on the span tests, the same overall effects of word-length found in the study on healthy adults described in the previous chapter, would be found in this study. As shown in Table 3.3, this prediction was confirmed: participants' recall was better when they had to recall short words than when they had to recall longer ones. This suggests that regardless of age, span is word-length -dependent (Baddeley et al., 1975).

Table 3. 3: Span tests - predictions and results

SPAN TASKS		PREDICTIONS	RESULTS	
SPAN FORWARD			YA and AE	A and E
GROUP		YA =AE; A=E	YA>AE	A=E
STIMULUS		No>N No>PN N=PN	No>N No>PN N=PN	No=N No>PN N=PN
LENGTH		2syll>3/5syll	2syll>3/5syll	2syll>3/5syll
STIMULUS X LENGTH	2 syllables	No>N No>PN N=PN	No>N No>PN N=PN	No>N No>PN N=PN
	3/5 syllables	No<N No=PN N=PN	No=N No=PN N=PN	No<N No<PN N=PN
STIMULUS X LENGTH X GROUP	2 syllables	n.s.	n.s.	No>N No>PN only in E N=PN
	3/5 syllables			No<N No<PN only in E N=PN
SPAN BACKWARDS			YA and AE	A and E
GROUP		YA =AE; A=E	YA>AE	A=E

Key: YA=Young adults (high education); AE=Adults (high education); A=Adults (low education); E=Elderly (low education); No=Number ; N=Noun; PN=Proper names; > = better performance; < = worse performance

When the effect of stimulus was analysed, the same overall effects found in the previous chapter were found in the young adults and adults (i.e. the two groups with higher education) with recall performance with numbers better than nouns and proper names. In the group of adults and elderly (i.e. the two groups with lower education), the difference was only found between recalling numbers and proper names. However, when further exploring this difference, it emerges that this can be explained by the fact that with longer items the opposite effect was found. As expected, stimulus and length were found to interact in all groups in the same way found in the previous chapter: one-digit numbers are recalled better than nouns and proper names of the same length; and two-digit numbers are recalled worse than nouns and proper names of the same length. The only results contrary to the previous chapter were that with longer items the group with higher education did not show a difference in recall between numbers and nouns and the group with lower education showed lower performance on recalling numbers compared to proper names. Moreover, the latter effects appeared to be evident only in the elderly group.

Since the groups had different levels of education, the effect of education on performance was investigated. When age is taken into account, the level of education has an effect only on the memory span when recalling longer items. This results suggests that there may be an effect of level of education on the performance of the PL. The results found could be an effect of both education and ageing: it could be speculated that dealing with two-digit numbers is more familiar for those with higher level of education, and this could have facilitated the recall in the group with higher education. Moreover an increased difficulty in dealing with two-digit numbers seem to be an effect of ageing, since the group of elderly showed more difficulties in recalling two digit numbers compared to their younger controls matched for level of education.

A further prediction was that lower performance would be found in the elderly group in the digit span backwards compared to their controls, but no differences would be found in the other span tests. It was in fact hypothesised that the additional control processes required to perform this task may impact on the hypothesised limited capacity of the CE in the group of elderly. Contrary to these expectations, minimal group differences were found between the adults and the elderly groups in the span tests. The only difference was found in the recall of bi-syllabic items, where the elderly group showed poorer performance than the group of adults. The fact that no difference was found with longer items, which presumably place more demands on maintenance, suggests that when there are sufficient resources available STM - and in particular the PL of WM - works better in adults than in elderly, but when more demands are posed on maintenance, adults' performance decreases and equals the performance of the elderly. This could suggest that the efficiency of maintenance processes reduce with ageing, in a way that mimics the effect of load on maintenance in younger adults.

Interestingly, the expected difference in the digit span backwards, where the demands on maintenance are coupled with demand on control processes, was not found. Furthermore, differences were found between the group of young adults and the group of adults in both the span tests and the digit span backwards. This could indicate a decrease in the functioning of the PL alone, although it is also consistent with previous findings that the rate of age-related performance decline was equivalent for both forward and backward span, which was interpreted as an indication that both tasks recruit central executive resources for successful task performance (Hester, Kinsella, & Ong, 2004). This is also consistent with Baddeley's (1996) suggestion that the demands made on the CE increase as the digit load increases past capacity. These results, considered together, suggest a decrease in both the PL and the CE functioning in the first half of the life span, with an additional decrease of the PL - suggested by a reduced length effect - in the elderly in the second half of the life span.

The possibility that ageing might selectively affect specific components of WM was also investigated. Van der Linden et al. (1994) argued that central executive resources decrease with aging and that this has to do with a reduction in the processing functions of the CE rather than its storage capacity. This idea is consistent with De Beni and Palladino's (2004) findings that older adults produce greater number of intrusion errors in an updating task, particularly when the updating demand is increased (suggesting an impairment in suppression and inhibition mechanisms). However, the authors also suggest a reduction in memory capacity resources with old age. According to Baddeley (1986), however, and in contrast with Van der Linden et al. (1994), ageing would provoke a decrease in the "total processing capacity" of the CE, but not in "its flexibility". If this was the case we would find a decrease in performance with ageing in recall performance during the updating task, but no increase in the same list intrusion errors produced. The failure to update relevant information could be in fact due to a reduction of the processing capacity, but, assuming that the control processes are intact, there should be no difficulty in inhibiting irrelevant information. If Van der Linden's interpretation was correct, however, in older adults we would find the opposite: an increase of intrusion errors but not necessarily a decrease of recall performance.

Hypothesising, in accordance with Baddeley (1986), that a CE executive defect in ageing would be related to its total processing capacity (regarded again here as the maintenance processes) and not to its flexibility (regarded here as the control processes), the predictions for this study were:

a) a decrease in recall performance (maintenance) with ageing, but no decrease in the ability to inhibit irrelevant information and therefore no increase in the production of errors due to the recall of an item "to be inhibited" (control);
b) a stronger effect of load on maintenance processes in elderly people compared to their controls

Moreover, as ageing is a continuous process, all predictions were tested comparing groups of three different age levels (young adults: 19-30 years of age;

adults: 34-55 years of age; and elderly: 61-85 years of age) in order to investigate at what point during ageing differences could be noticed.

The overall effects found in chapter 2 were expected in the updating tasks. Indeed, as shown in Table 3.4, the same main effects found in the group of adults studied in the previous chapter were found in the recall performance and in the production of invention and omission errors in all age levels studied here. The main findings are that recall performance on the updating task is affected by load on maintenance. The pattern of results suggests that there is a threshold for the number of items that WM can hold and manipulate efficiently at any one time, and especially when there is loading on control processes, with better performance when fewer items have to be suppressed/inhibited. These results are consistent with the predictions of this study, with the idea of a storage capacity of the central executive and also with suggestions that success in remembering relevant information and in suppressing irrelevant information in WM is related to the availability of resources to the WM system (Engle et al., 1992; Conway et al., 1999). Also, similar effects of stimuli were found: performance when recalling nouns is better than with numbers. This suggests that for these measures the conclusions discussed in Chapter 2 are applicable across the whole life span.

In contrast, a different pattern is evident for the production of same list intrusion errors. While the same effect of load on control processes is evident (with fewer errors produced when the load was lower), the production of this kind of error in overall group of adults and elderly people was modulated by the load on maintenance processes (with increasingly more errors produced with an increase in demand) and by the stimulus to be recalled (with more errors produced when recalling words than when recalling numbers). These effects interacted with one another: the effect of load on control processes is only present when the highest demands are posed on the maintenance process. Moreover, the unexpected result of more same list intrusion errors produced when recalling words than when recalling numbers is only found when either the load on control processes or the load on maintenance processes is high. This suggests that when high demands (either of maintenance or of control) are posed on the CE, the control processes allowing the discarding of no-longer-relevant items fail, and particularly so with words. The reason for this unexpected effect of stimulus in the less educated group composed by adults and elderly people, remains unexplained by this study.

As far as previous list intrusion errors are concerned, similar effects of load on maintenance and stimulus as in the previous chapter are evident. Furthermore, an effect of load on control processes is present in all groups. This indicates that more errors of this kind are produced with higher load on control processes. This result was not found in the previous study. It is possible that the effects of the present study were more powerful due to the greater number of participants.

Table 3. 4: Updating task - Overall effects - predictions and results

		Previous study	YA&AE (high education)	A&E (low education)
RECALL	INHIBITION	LI>HI	LI>HI	LI>HI
	RECALL	Quadratic decrease	Quadratic decrease	Quadratic decrease
	STIMULUS	W>N	W>N	W>N
	INHIB X RECALL	LI>HI with R4	n.s.	LI>HI with R3;R4
	INHIB X STIMULUS	n.s.	n.s.	n.s.

		Previous study	YA&AE (high education)	A&E (low education)
	RECALL X STIMULUS	W>N with R4	W>N with R4	W>N only with R4
	INHIB X REC X STIM	n.s.	n.s.	With W: LI>HI with R4 With N: LI>HI with R3
SAME LIST INTRUSIONS	INHIBITION	LI>HI	LI>HI	LI>HI
	RECALL	n.s.	n.s.	Linear decrease
	STIMULUS	n.s.	n.s.	W<N
	INHIB X RECALL	n.s.	n.s.	LI>HI only with R4
	INHIB X STIMULUS	n.s.	n.s.	W<N only with HI
	RECALL X STIMULUS	n.s.	n.s.	W<N only with R3; R4
	INHIB X REC X STIM	n.s.	n.s.	n.s.
PREVIOUS LIST INTRUSIONS	INHIBITION	n.s.	LI>HI	LI>HI
	RECALL	Quadratic decrease	Quadratic decrease	Quadratic decrease
	STIMULUS	W>N	W>N	W>N
	INHIB X RECALL	n.s.	n.s.	LI>HI with R2; R3
	INHIB X STIMULUS	n.s.	n.s.	n.s.
	RECALL X STIMULUS	W>N with R3 and R4	W>N with R4	W>N with R2; R4
	INHIB X REC X STIM	n.s.	n.s.	With W: LI=HI With N: LI>HI with R3
INVENTIONS	INHIBITION	n.s.	n.s.	n.s.
	RECALL	Linear decrease	Linear decrease	Linear decrease
	STIMULUS	W>N	W>N	W>N
	INHIB X RECALL	n.s.	n.s.	LI>HI with R3
	INHIB X STIMULUS	n.s.	n.s.	n.s.
	RECALL X STIMULUS	W>N with R4	W>N with R4	W>N with R3; R4
	INHIB X REC X STIM	n.s.	n.s.	With LI: W>N with R4 With HI: W>N with R3
OMISSIONS	INHIBITION	LI>HI	LI>HI	LI>HI
	RECALL	Quadratic decrease	Quadratic decrease	Quadratic decrease
	STIMULUS	n.s.	W>N	n.s.
	INHIB X RECALL	n.s.	n.s.	LI>HI with R2; R4
	INHIB X STIMULUS	n.s.	n.s.	n.s.
	RECALL X STIMULUS	W>N with R4	W>N with R4	n.s.
	INHIB X REC X STIM	n.s.	n.s.	n.s.

Key: LI=Low Inhibition; HI=High Inhibition; R1, R2, R3, R4=1 item to recall, 2 items to recall etc.; W=Words (i.e. nouns); N=Numbers; > = better performance (i.e. more items recalled or fewer errors); < = worse performance (i.e. fewer items recalled or more errors); Decrease= decrease in performance (i.e. decrease in recall or increase in errors); n.s. = not significant

Table 3.5 summarises the predictions and results on the effects of group in the updating task. Examining the main predictions for the updating task, as expected, a decrease in recall performance (maintenance) was found with ageing. This decrease appears to be a gradual process that is already evident in mid-aged adults (compared with younger adults) and that continues into old age. This result is consistent with Baddeley's (1986) suggestion that ageing provokes a decrease in the "total processing capacity" of the CE but not with Van der Linden et al.'s (1994) argument that the reduction of CE resources with aging is not due to the CE capacity.

A decrease in control processes with age was expected, in accordance with Baddeley (1986). However, no decrease was found in the group of elderly people compared to the group of adults, which further argues against Van der Linden et al.'s (1994) suggestion that the reduction of CE resources with aging is due to a reduction in the processing functions of the central executive. It is also incompatible with Hasher and Zacks' (1988) suggestion that older adults have difficulty in inhibiting irrelevant and suppressing no longer relevant information. Interestingly, however, the group of adults produce more intrusion errors from the same list compared to the younger group, which is considered to be an index of the ability to inhibit irrelevant incoming information. In particular, this effect is present when the load on control processes is higher, which suggests that in the first half of the life span the efficiency of control mechanisms of WM seems to reduce when high demands are placed on this process. This appears to stabilise with further ageing, which would explain why the effect was not found when comparing adults with elderly. Moreover, different effects emerged when recalling nouns compared to numbers. When recalling nouns, the younger group did not produce any intrusion errors from the same list, while the group of adults produced increasingly more of these errors with the increase of load on maintenance. When recalling numbers, instead, younger adults and adults showed a similar production of intrusion errors from the same list. This may suggest that recalling numbers increases the demands on maintenance processes, which therefore taxes control processes even in younger adults.

Another prediction of the study was that a stronger effect of load on maintenance processes would be found in elderly people compared to their controls. Such an effect was not present.

No difference between groups was found in previous list intrusion errors (i.e. the intrusion of old non suppressed information from LTM), suggesting that there is not a generalised impact of ageing on memory, but that the differences found are specific to WM. Interestingly, elderly people produce more invention errors than adults when recalling numbers.

Table 3. 5: Updating task - Effects of group - predictions and results

		PREDICTIONS		RESULTS	
		YA&AE (high education)	A&E (low education)	YA&AE (high education)	A&E (low education)
RECALL	GROUP	n.s.	A>E	YA>AE	A>E
	INHIBITION X GROUP	n.s.	n.s.	n.s.	n.s.
	RECALL X GROUP	n.s.	A>E with high load	n.s.	n.s.
	STIMULUS X GROUP	n.s.	n.s.	n.s.	n.s.
	INHIB X REC X GROUP	n.s.	-	n.s.	n.s.
	INHIB X STIM X GROUP	n.s.	-	n.s.	n.s.
	REC X STIM X GROUP	n.s.	-	n.s.	n.s.
	INHIB X REC X	n.s.	-	n.s.	n.s.

		PREDICTIONS		RESULTS	
		YA&AE (high education)	A&E (low education)	YA&AE (high education)	A&E (low education)
	STIM X GROUP				
SAME LIST INTRUSIONS	GROUP	n.s.	n.s.	YA>AE	n.s.
	INHIBITION X GROUP	n.s.	n.s.	YA>AE with HI	n.s.
	RECALL X GROUP	n.s.	A>E with high load	n.s.	n.s.
	STIMULUS X GROUP	n.s.	n.s.	n.s.	n.s.
	INHIB X REC X GROUP	-	-	n.s.	n.s.
	INHIB X STIM X GROUP	-	-	n.s.	n.s.
	REC X STIM X GROUP	-	-	With W: YA>AE only with R3; R4 With N: YA=AE	n.s.
	INHIB X REC X STIM X GROUP	-	-	n.s.	n.s.

Key: YA=Young adults (high education); AE=Adults (high education); A=Adults (low education); E=Elderly (low education); LI=Low Inhibition; HI=High Inhibition; R1, R2, R3, R4=1 item to recall, 2 items to recall etc.; W=Words (i.e. nouns); N=Numbers; > = better performance (i.e. more items recalled or fewer errors); < = worse performance (i.e. fewer items recalled or more errors); Decrease= decrease in performance (i.e. decrease in recall or increase in errors); n.s. = not significant

The results found in the updating task match those found in the span tests: there is evidence that a gradual decrease in recall maintenance processes with ageing, that can be seen in mid-aged adults and continues into old age. Taken together these results suggest that in the first half of the life span the efficiency of control mechanisms of WM seems to reduce but this stabilises with further ageing.

These results partly support Baddeley's (1986) suggestion that ageing provokes a decrease in the "total processing capacity" of the CE or, in Van der Linden et al.'s (1994) view, the "CE storage". They also partly support Van der Linden et al. (1994) and Hasher and Zacks' (1988) suggestions that aging is related to a decrease in the processing functions of the central executive. An important point of divergence from the latter ideas, however, is that the changes these authors suggest happen in older age, actually seem to emerge much earlier in life.

Obviously, since the groups investigated in this study were quite small, these results would need to be replicated on a larger scale in order to make stronger conclusions on the effects on ageing on the control processes of WM, but the suggestion that differences emerge early during the ageing process is unexpected, and suggests further avenues for research such as conducting longitudinal studies in order to evaluate the trajectory of functioning of WM over the life-span.

In summary, the data from this study contributes to our understanding of how WM processes, and more specifically updating and inhibition, are affected by the aging process. An advantage of the study is that it looked at various stages of the life-span to try to highlight more fine-grained differences due to age. However, the results are limited by the fact that the study was not longitudinal and that the group sizes were not large. Moreover, the study only looked at the effects of ageing in healthy participants. This leaves unanswered a question on the effects of "abnormal" ageing on maintenance and control processes of WM. The next chapter will attempt to answer this question, by also looking at the effects of WM on mental calculation, a complex cognitive function heavily relying on WM.

CHAPTER 4: WORKING MEMORY AND CALCULATION: A STUDY ON EARLY DEMENTIA OF THE ALZHEIMER'S TYPE (DAT)

4.1. Introduction

The first aim of this study was to investigate the processes studied in the previous chapter in a new population, those with DAT, with attention to the possibility that DAT might selectively affect specific components of WM. Another aim of this study was to assess whether there is any difference between DAT patients and normal elderly participants in performance on numerical and calculation tasks. A final question addressed by this study is whether there is a relationship between numerical and calculation impairments (if any) in early DAT patients and the functioning of WM, and if this relationship is attributable to certain components of WM more than to others.

4.1.1. Working Memory and Dementia of the Alzheimer's Type (DAT)

Several studies show that WM deteriorates with ageing. Baddeley (1986), for example, suggests that an important characteristic of ageing is a decline in the capacity of the CE. This is increasingly evident in the case of abnormal aging (e.g. in senile dementia) and in the dysexecutive frontal syndrome. Baddeley (1986) considered different aspects of the CE as differently affected in these populations. The main distinction is between the total processing capacity of the CE and its flexibility. From this perspective, the dysexecutive syndrome would mainly involve deficient control processes, whereas normal aging would involve a drop in the overall processing capacity, and Dementia of the Alzheimer's Type (DAT) would involve both deficits.

Van der Linden et al. (1994) studied age-related differences in the ability of updating WM. Memory updating seems to be dependent on the CE and was investigated with the running memory span task (Morris & Jones, 1990), for which the PL is also required for articulatory rehearsal. Van der Linden et al.'s (1994) results support the hypothesis that in older participants CE resources are reduced. In particular, processing resources of the CE are affected more than its storage capacity, a finding which is in opposition to Baddeley's (1986) suggestion. This means that updating processes do operate normally if there are enough resources available to the responsible system (CE).

An interesting finding from Li (1997), is that aging involves an impairment in the ability to ignore irrelevant information. This further suggests that what declines with age are control processes more than processing capacity.

As far as DAT is concerned, Morris (1984) suggests that the PL is functioning properly but the problem is the capacity to store information while simultaneously processing a heavy cognitive load (Morris, 1986), a function which is expected to be dependent on the CE (Baddeley, Logie, Bressi, DellaSala, & Spinnler, 1986). A study investigating verbal and spatial memory spans in DAT (Carlesimo, Fadda, Lorusso, & Caltagirone, 1994) also showed that the PL is working and that the problem are the deficient processing resources of the CE. More recent studies (Vecchi, Saveriano, & Paciaroni, 1998/1999) highlighted the importance, in evaluating patients with DAT, of distinguishing between tasks that require passive storage and those in which an active manipulation of the information is required (the latter condition is the one in which patients are particularly impaired, regardless of the type of material used).

It has been demonstrated that people with DAT, along with episodic LTM problems, suffer from attentional deficits (Perry & Hodges, 1999). This suggests that in these patients the central executive might be impaired. The dementing process in DAT requires progressively more control resources, even for tasks that the normal elderly run quasi-automatically (Spinnler, 1991). Because of this increasing demand on the CE functions of time-and accuracy- sharing, patients are sensitive to tasks in which CE involvement is particularly high (Jorm, 1986). Baddeley et al. (1986) studied a group of DAT patients using a tracking task as the primary task, and three different concurrent tasks: articulatory suppression, simple reaction time to a tone, auditory digit span. They demonstrated that DAT patients had particularly impaired functioning of the CE, which was reflected by their inability to perform two concurrent tasks simultaneously. Baddeley et al. (1991) replicated this finding with a longitudinal study, supporting the hypothesis of a deficit of the CE in patients with DAT. Spinnler et al. (1988) used free recall and verbal and non-verbal span to test DAT patients, normal elderly participants and normal young participants. Their results confirm the presence of a CE deficit in DAT.

The pattern of memory deficits in DAT patients is quite peculiar: the STM problems combine with an additional difficulty in establishing new material in LTM storage (Miller, 1973). DAT patients are particularly impaired in the ability to co-ordinate the performance of two concurrently performed tasks. The best interpretation of this kind of deficit is to assume an impairment of the CE, time-sharing component of WM (Della Sala, Logie, & Spinnler, 1992).

Belleville et al. (1996) examined the verbal and attentional components of WM, in patients with DAT, normal elderly and young controls. This study supports previous findings of an impairment of the CE in patients. However this study also highlighted, in a sub-group of patients, a deficit at the phonological processing level (even if the rehearsal procedure seems not to be impaired). A way to explain this difference with previous findings is that the patients studied by Belleville et al. (1996) were quite severe. This could mean that the CE is the first component of WM to be affected, and with the progression of the disease, the other sub-system gradually becomes impaired.

To try to disentangle these contradictory results, Collette, Van der Linden, Bechet and Salmon (1998) re-evaluated the functioning of the PL and the CE in a single group of patients with DAT, comparing them with a group of elderly controls. Their results suggest that several components of WM (the phonological store, articulatory rehearsal system and the CE mechanism) can be affected by DAT but that not necessarily all aspects of the CE are affected.

Other studies seem to support this, finding that patients show a deficit in the CE as well as in the PL (Collette, Van der Linden, Bechet, & Salmon, 1999). However the latter seems to be a consequence of the progression of the disease.

In a study by Borgo, Giovannini, Moro, Semenza, Arcicasa and Zaramella (2003) DAT patients were relatively more sensitive to tasks involving the maintenance of relevant information, compared to frontal patients who seemed to be worse in inhibiting irrelevant, interfering, information.

4.1.2 Numerical processes and DAT

In recent years the field of calculation deficits has been increasingly investigated. From a neuropsychological point of view, most of the research concerns the study of patients with focal brain lesions. Only a limited number of studies involve dementia patients with specific numerical deficits. Group studies focused on the role of limited cognitive resources (Parlato, Lopez, Panisset, Iavarone, Grafman, & Boller, 1992; Deloche, Hannequin, Carlomagno, Angiel, Dordain, Pasquier, Pellat, Denis, Desi, Beauchamp, Metz-Lutz, Cesaro, & Seron, 1995; Mantovan, Delazer, Ermani, & Denes, 1999). Single-case, follow-up studies mainly focused on the progressive decline of numerical abilities. These studies typically concerned numerical transcoding (Tegner & Nyback, 1990; Noel & Seron, 1993; Cipolotti, 1995; Noel & Seron, 1995; Kessler & Kalbe, 1996; Thioux et al., 1999) and calculation abilities (Grafman, Kampen, Rosenberg, Salazar, & Boller, 1989; Marterer, Danielczyk, Simanyi, & Fischer, 1996; Girelli, Luzzatti, Annoni, & Vecchi, 1999; Mantovan et al., 1999; Duverne, Lemaire, & Michel, 2003).

"Transcoding" refers to the ability to translate numerals from one code to another (oral/written; Arabic/verbal), and it is an operation required in many daily activities (e.g. writing down a telephone number that someone is dictating to us (oral/written) or writing "one hundred and fifty pounds" on a cheque to pay a bill that we received). Several models have been proposed that try to explain the processes involved in transcoding. Mc Closkey and colleagues developed a model of number processing incorporating both transcoding and calculation (McCloskey, Caramazza, & Basili, 1985; McCloskey, Sokol, & Goodman, 1986; McCloskey, Sokol, Goodman, & Caramazza, 1990; McCloskey, 1992). According to this model an abstract internal representation underlies numerical operations, including transcoding and calculation. According to the model, therefore, number transcoding occurs via a single semantic route that includes the abstract internal representation. This assumption has been challenged and alternative models have been proposed. Deloche and Seron (1982; 1987) and

Cohen and Dehaene (1991) proposed that the transcoding from Arabic to verbal numerals can occur directly without the mediation of the abstract code and through a single "asemantic" route, whereas Cohen, Dehaene and Verstichel (1994) proposed a model with both semantic and asemantic transcoding routes. They suggested that reading familiar Arabic numerals would involve a semantic transcoding route and reading unfamiliar numerals would involve an asemantic route. Cipolotti also proposed a model with independent (semantic and asemantic) and mutually inhibiting routes for number processing that are activated differentially depending on task demands (Cipolotti, 1995; Cipolotti & Butterworth, 1995). Transcoding tasks preferentially activate the asemantic transcoding route.

Several cognitive mechanisms modulate transcoding, therefore the study of its impairment in DAT patients has been very useful in understanding the structure of these mechanisms. A characteristic error made by patients and repeatedly reported in the literature (Tegner & Nyback, 1990; Kessler & Kalbe, 1996; Thioux et al., 1999) is the intrusion of the Arabic code in the verbal code. This could be due to a failure to suppress a more automatized behaviour (to use arabic numerals) (Tegner & Nyback, 1990). The problem with this explanation is that sometimes the opposite problem emerges. Kessler and Kalbe (1996) reported that usually, the intrusions were elements of the source code in the target code. They interpreted this finding as a failure of control mechanisms. The problem with this explanation is that the deficit can be unidirectional (Thioux et al., 1999) which cannot be explained by a failure of the Supervisory attentional System (SAS).

The studies of dementia and calculation have shown the functional independence of various abilities underlying calculation (i.e. retrieval of arithmetic facts, knowledge and application of procedures). Group studies (Mantovan et al., 1999) and single case follow-ups (Grafman et al., 1989; Girelli et al., 1999) suggest an inefficiency of executive control (deficient monitoring and inhibition mechanisms) as one cause of patients' errors with arithmetical procedures. Grafman et al.'s (1989) patient showed a dissociation between spared declarative and impaired procedural knowledge. Mantovan et al. (1999) suggest that patients' errors in complex calculation arise from a monitoring deficit and not from poor calculation algorithms. Girelli et al.'s (1999) patient showed, with disease progression, increasing difficulties in written calculation due to a failure in the execution of the appropriate algorithm, supporting the idea of a functional dissociation between procedural and declarative knowledge within the same operation.

A few studies explored more basic numerical competencies, such as dot counting and number comparison. Kaufmann, Montanes, Jacquier, Matallana, Eibl and Delazer (2002) studied the relationship between basic numerical knowledge and arithmetic (facts and procedures) in early DAT. In most patients, basic numerical knowledge (e.g. distance effect in number comparison, and subitizing in naming numerosities) was found to be preserved whereas facts and procedural knowledge was impaired. Therefore a dissociation was found between basic numerical skills and arithmetical knowledge, suggesting that basic numerical knowledge is not necessary for maintaining arithmetical facts.

What emerges from all these studies is that the pattern of preserved and impaired abilities can vary enormously across patients. Although some group studies show trends in the data, an analysis at the single-participant level highlights high variability between individuals' performance, with the occasional presence of double dissociations (Girelli & Delazer, 2001).

4.1.3. Hypotheses

This study aimed to investigate the possibility that DAT might selectively affect specific components of WM. More specifically, using the tasks investigated in the previous study, a poorer performance on both recall (maintenance) and inhibition of irrelevant information (control) in people with DAT compared to their (age-matched) controls is expected, based on the finding that several components of WM (phonological store, articulatory rehearsal system and CE mechanism) can be affected by DAT (Collette et al.,1998). Previous studies show that patients have a deficit in the CE as well as in the PL (Belleville et al., 1996; Collette et al., 1999), but that deficits of the PL seemed to be a consequence of the progression of the disease. All participants who took part in the present study were at the initial stages of the disease, and therefore no deficit of the PL was expected. In addition, this study investigates distinct aspects of the CE: its maintenance processes and its control processes. In this study, they are both expected to be affected by DAT.

Moreover, the predictions are that recall performance will be more affected by load on maintenance processes in people with DAT compared to their controls, and that performance on both recall and inhibition of irrelevant information will be more affected by load on control processes in people with DAT compared with controls. This is consistent with the idea that in patients with DAT progressively more control resources are required, even for tasks that are almost automatic for healthy older adults (Spinnler, 1991). Because of this increasing demand on CE functions, people with DAT are sensitive to tasks in which CE involvement is particularly high (Jorm, 1986).

Lower performance of DAT patients compared to controls is also expected in the digit span backwards task. No other differences between the groups were expected in the span tests, in accordance with the idea that PL is not affected in DAT, at least at the initial stages of the disease (Carlesimo et al., 1994; Collette, Van der Linden, Bechet, Belleville, & Salmon, 1998).

Another aim of this study was to assess whether there is any difference between DAT patients and healthy elderly participants in performance on numerical and calculation tasks. In order to do so, performance on measures of numerical and calculation processing were measured in a group of participants with DAT. The number and calculation tasks have been chosen to allow the detection of various different numerical and calculation abilities, and to assess specific impairments in them. The predictions are that participants with DAT will perform poorly in the transcoding tasks (and in particular, in accordance with Kessler & Kalbe (1996), they are expected to produce intrusions of the source code in the target code, due to a failure of control mechanisms). The same is expected in complex mental calculation (due to an inefficiency of executive control (Grafman et al., 1989; Girelli et al., 1999; Mantovan et al., 1999)), compared to controls. No difference is expected between groups in performance on the arithmetical facts (due to intact declarative knowledge (Girelli et al., 1999)).

A final question addressed by this study is whether there is a relationship between numerical and calculation impairments (if any) in early DAT patients and the functioning of WM, and if this relationship is attributable to certain components of WM more than to others. Patients' errors in some calculation tasks could, in fact, be caused by a general problem in monitoring arithmetical procedures, possibly the inability to update relevant information and inhibit information no longer useful at different stages of calculation. According to this idea the calculation system would be affected earlier than others by this WM impairment because of the greater load on executive functions and the higher demand of monitoring it requires. If the difficulty with calculation in this group stemmed from a monitoring problem (arguably a deficit in the control processes), this would most likely produce a varied pattern of errors that could happen at different stages of the procedure (Semenza, Miceli, & Girelli, 1997). This could explain the non-heterogeneous pattern of calculation errors shown by DAT patients and reported in the literature. Calculation tasks have been reported to be reliable early predictors of an ongoing dementia process (Mantovan et al., 1999; Girelli & Delazer, 2001). The finding of a close relationship between the performance of DAT patients in these and WM tasks would reveal that both could be useful tools for early diagnosis.

A clinical implication of this research would be the addition of a WM task that enables us to distinguish between maintenance and control processes, together with some numerical and calculation tasks, in neuropsychological batteries used for early diagnosis of DAT.

4.2. Method

4.2.1. Participants

Forty-four individuals participated in this study. Nineteen were patients recruited through the Institute of Clinical Psychiatry of the University of Trieste (Italy) where they were followed by psychiatrists and neuropsychologists as a part of the CRONOS project for the early diagnosis of DAT. Patients' inclusion and exclusion followed the DSM-IV (APA, 1994) and the NINCS–ADRDA criteria (McKhann, Drachman, Folstein, Katzman, Price, & Stadlan, 1984), neuroimaging examinations (CT and MRI reports compatible with a diagnosis of dementia of the Alzheimer's type) and neuropsychological evaluation. The degree of cognitive deterioration was evaluated through the Mini-Mental State Examination (Folstein, Folstein, & McHugh, 1975) and through an evaluation of the available data from previous neuropsychological testing (including tests of memory and executive functions). Unfortunately the neuropsychological data were not available at the time of writing the present dissertation. Inclusion criteria were a diagnosis of very mild DAT (i.e. a score in the MMSE corrected for age and educational level over 20). Exclusion criteria for the study were present or past psychiatric problems; suspect vascular dementia; and sensorial problems which could interfere with the administration of tests. Fifteen healthy elderly controls, matched to the patients' group for age and education level, participated in the study. Following the study described in chapter three, we were interested in investigating what are the effects of DAT on WM, in order to compare the effects of normal and abnormal ageing on this cognitive function. Therefore, ten healthy adults participated in the study undergoing the WM tasks (but not the numerical and calculation tasks). They were matched to the other two groups for level of education. Table 4.1 illustrates age and education of participants in the three groups.

Table 4. 1: Participants'age and education

	Mean (Standard Deviation)		
	DAT (N=19)	**EC** (N=15)	**AC** (N=10)
Age	76.5 (5.37)	71.3 (7.48)	44.3 (5.06)
Education	9.4 (2.71)	7.5 (4.16)	8.0 (0.00)
Male : Female Ratio	5:14	6:9	5:5

4.2.2. Neuropsychological screening

The DAT group were screened with a comprehensive neuropsychological battery as part of their diagnostic and treatment program within the CRONOS project.

For the present study they were administered the MMSE (Folstein et al., 1975), the Raven Progessive Coloured Matrices (Raven, 1985) and verbal digit span (Wechsler, 1997). Participants' performance on the screening tasks in illustrated in Table 4.2.

Table 4. 2: Participants' neurpsychological screening

	Mean (Standard Deviation)
	DAT (N=19)
MMSE (corrected)	24.0 (3.26)
RCPM (max score:36)	21.9 (5.45)
Digit span forward	5.0 (1.43)
Digit span backwards	4.5 (1.18)

Participants were required to have a verbal digit span forward of at least three digits and backwards of at least two digits. This condition was necessary to ensure effective administration of the WM task (i.e. making sure that they would understand the instructions and would not perform at floor level).

4.2.3. Experimental Tasks

The administration of the tests was divided into two parts for each individual participant, each lasting for one hour with a one-week interval between the two. This was to prevent excessive fatigue of the participants, and the repetition of stimuli within the same session.

4.2.3.1. Working Memory Tasks

SPAN TESTS

The same stimuli and procedures were used as in the study on healthy participants (see Chapter 2).

UPDATING TASK

The same stimuli and procedures were used as in the study on healthy participants (see Chapter 2).

4.2.3.2. Numerical Tasks

Numerical tasks consisted of: reading written Arabic numerals; writing Arabic numerals to dictation; transcoding from Arabic numerals to written verbal numbers and vice versa; reading written verbal numerals; writing verbal numerals to dictation, writing words to dictation (as a control for the previous test) (see Appendix III). These tests were chosen both to check the basic numerical abilities (e.g. comprehension of numerals and comparison of magnitudes), and to evaluate performance on tasks involving inhibition of irrelevant code (Kessler & Kalbe, 1996; Thioux et al., 1999).

WRITING NUMERALS

Twelve numbers were presented verbally one by one by the examiner. The participant was required to write them in Arabic format or in Verbal format on a piece of paper. The stimuli were the same in the two tasks, which were presented in different sessions. The numerals were: one one-digit; one teen; one ten; one two-digit; four three-digit (one without zero, one with zero in second position, one with zero in third position and one with a zero in second and a zero in third position); and four four-digit (one without zero, one with zero in second position, one with zero in third position and one with a zero in fourth position).

As a control for the previous task, in order to verify whether there was a problem with writing to dictation itself or there was a more specific problem with writing numerals to dictation, twelve words were presented verbally one by one by the examiner. The participant was required to write them on a piece of paper. The words were selected trying to match the length in syllables of the corresponding number words in the previous task. Ten of them were compound names, to try to match the complexity of teens, two-digit, and three-digit numbers.

READING NUMERALS AND TRANSCODING TASKS

- *Arabic to Verbal*

Twenty written Arabic numerals were visually presented one by one on the centre of a computer screen. The numerals were: six one-digit; two teens; two tens; two two-digit; four three-digit (one without zero, one with zero in second position, one with zero in third position and one with a zero in second position and a zero in third position); four four-digit (one without zero, one with zero in second position, one with zero in third position, and one with a zero in second, a zero in third and a zero in fourth position). The participant was asked to read them aloud and to write them in verbal formats, one by one. The stimuli were presented until the participants finished their response.

- *Verbal to Arabic*

The same numbers were presented with the same procedure but as written words (e.g. ONE, THIRTEEN). The participants were asked to read them aloud and write them in Arabic format.

4.2.3.3. Calculation Tasks

Calculation tasks consisted of: arithmetical fact retrieval and complex mental calculation (See Appendix IV)

ARITHMETICAL FACTS

Thirty-two problems (ten additions, ten subtractions, and twelve multiplications) were visually presented one by one on the centre of a computer screen. The problems were simple arithmetical facts and both operands were one-digit. Four of the addition problems had the first addend smaller than the second and four had the second one smaller. For each category half of the results was bigger than 10 and half was smaller. Two problems contained a rule (i.e. adding zero). In the subtraction problems, one-digit numbers from 0 to 9 were used and the result was always less than 10. Two of the subtractions contained a rule (i.e.subtracting zero). Of the multiplication problems, five had the first operand smaller than the second one and five had the second one smaller (all the operands were one-digit, from 0 to 9). Four of the problems were rules (two involving the number one and two involving zero; in half of them the smaller number was in first position in half was in the second position). Half of the problems had a result smaller than 10 and half had a result bigger than 10. The participant was asked to answer verbally as quickly and accurately as possible.

Jackson & Warrington test

The stimuli from the Jackson & Warrington (1986) test were used. This is a graded difficulty arithmetic test consisting of 14 additions and 14 subtractions orally presented by the examiner. In the original task the participant is asked to give a verbal answer to the problem as quickly as possible, since the test is timed and only answers given within the first ten seconds are considered.

For this study the same stimuli and procedures were used apart from the timing, which was not constrained. The reason for this choice was that this test was chosen as a suitable task to judge the ability of the participants in maintaining and elaborate the information (which are operations involving WM) and the timing pressure on the participants was considered unnecessary.

Complex Mental Calculation

Another task was developed in order to study complex mental calculation with visual (and not verbal) presentation. The reason of this choice was to have a task that would require to the participant to perform a complex mental calculation, without loading the phonological loop. It has in fact been shown by Furst and Hitch (2000) that articulatory suppression (a task requiring the use of phonological loop) had no effect on the performance on solving a mental sum when the numbers were visible for the time required by the participants to solve the operation. Moreover Noel et al. (2001) suggested that the PL is the component involved in the temporary storage of addends, and therefore not having to temporarily store the addends, would allow the examination of the WM components involved in the actual process of mental calculation.

The participant was presented with a series of sixty-seven increasingly difficult operations (thirty-four additions and thirty-three subtractions) in the centre of a computer screen.

All the items of the Jackson & Warrington (1986) test were presented (in different sessions) in order to evaluate differences in performance due to the presentation modality (i.e. verbal vs. visual).

The difficulty was related to the number of carryings or borrowings required to solve the operation and to the length in digits of the operands. As far as carryings and borrowings are concerned, twelve additions requiring no carryings, fourteen additions requiring one carrying, eight additions requiring two carryings; fifteen subtractions requiring no borrowing, fourteen subtractions requiring one borrowing, and four subtractions requiring two borrowings were presented. As far as the length in digits of the operands is concerned, out of the thirty-four additions, one item required to add a one-digit number to another one-digit number, ten items required to add a two-digit number to a one-digit number, ten items required to add a two-digit number to another two-digit number, nine items required to add a three-digit number to another three-digit number, four items required to add a three-digit number to another three-digit number. Of the thirty-three subtractions, one item required to subtract a one-digit number from another one-digit number, ten items required to subtract a one-digit number from a two-digit number, ten items required to subtract a two-digit number from another two-digit number, nine items required to subtract a two-digit number from a three-digit number, and finally three items required to subtract a three-digit number from another three-digit number.

In both the numerical and the calculation tasks the percentage of hits (correct answers) was considered.

4.3. Results

4.3.1. Working Memory Tasks

4.3.1.1. Span Tests

Four participants of the DAT group were only administered the digit span forward and the digit span backwards. The missing values were analyzed as such with the statistical analysis package SPSS. Due to the violation of normality assumption for the variables tested, a non-parametric analysis was performed.

GROUP DIFFERENCES

A Kruskal-Wallis Test was conducted comparing the span (i.e. number of items correctly recalled) in the three groups (DAT, EC, and AC). As it can be observed in Figure 4.1, a significant difference was found between groups on the digit span backwards [$\chi^2(2) = 7.68$; $p<.05$]; the 2-syllable nouns span [$\chi^2(2) = 10.19$; $p<.01$]; the 2-digit span [$\chi^2(2) = 9.34$; $p<.01$]; the 3/5-syllable nouns span [$\chi^2(2) = 11.51$; $p<.005$]; the 2-syllable proper names span [$\chi^2(2) = 9.06$; $p<.02$]; and the 3-5 syllable proper names span [$\chi^2(2) = 7.39$; $p<.05$]. The groups do not differ on the digit span forward[99]. Three Mann-Whitney Tests were conducted, comparing performance of each group with the other. The results show that the DAT group differs from the EC group on the 3/5-syllable nouns span [Mann-Whitney U-Test = 61.00; $p < .05$], and on the 3/5-syllable proper names span [Mann-Whitney U-Test = 52.50; $p < .02$], but not on the other tests[100]. The DAT

[99] [$\chi^2(2) = 5.19$; $p>0.05$]

[100] digit span forward [Mann-Whitney U-Test = 107.00; $p>0.05$];digit span backwards [Mann-Whitney U-Test = 86.00; $p = 0.051$.]; 2-syllable nouns span [Mann-Whitney U-Test = 75.50; $p>0.05$]; 2-digit span [Mann-Whitney U-Test = 90.00; $p>0.05$]; and 2-syllable proper names span [Mann-Whitney U-Test = 96.00; $p>0.05$]

group differs from the AC group on all the tests (digit span backwards [Mann-Whitney U-Test = 42.00; $p < .02$]; 2-syllable nouns span [Mann-Whitney U-Test = 23.00; $p < .005$]; 2-digit span [Mann-Whitney U-Test = 25.00; $p < .005$]; 3/5-syllable nouns span [Mann-Whitney U-Test = 19.50; $p < .002$]; 2-syllable proper names span [Mann-Whitney U-Test = 29.00; $p < .01$]; 3-5 syllable proper names span [Mann-Whitney U-Test = 42.00; $p < .05$]), except for the digit span forward[101].

The EC group differs from the AC group on the 2-syllable nouns span [Mann-Whitney U-Test = 35.00; $p < .05$], and on the 2-syllable proper names span [Mann-Whitney U-Test = 27.50; $p < .02$], but not on the other tests[102].

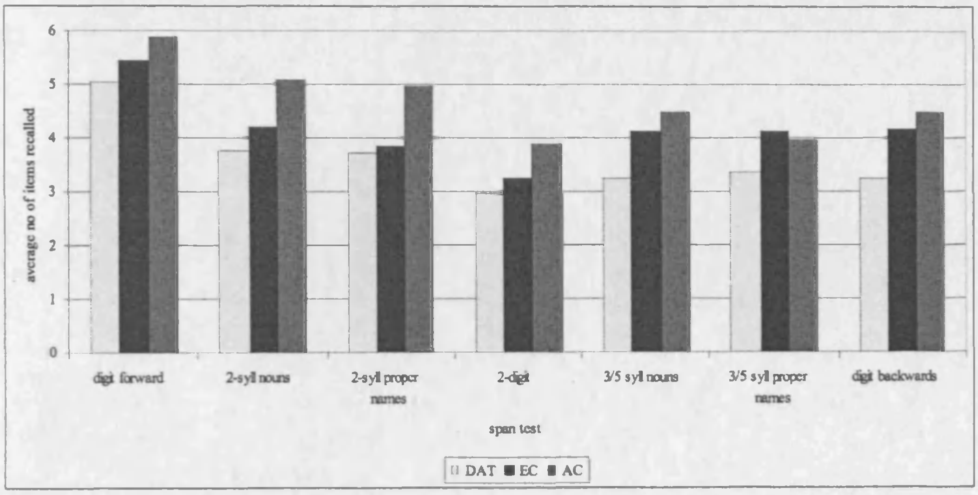

Figure 4. 1: Span tests - comparison between DAT, EC, and AC

THE EFFECT OF STIMULUS

In order to investigate the impact of the type of stimuli on the performance on the span tests, a Friedman Test was performed comparing the performance on the span tests involving two-syllable items (i.e. digit span forward, 2-syllable

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101 [Mann-Whitney U-Test = 52.50; $p = .05$]

102 digit span forward [Mann-Whitney U-Test = 50.00; $p>0.05$];digit span backwards [Mann-Whitney U-Test = 64.50; $p = 0.051$.]; 2-digit span [Mann-Whitney U-Test = 41.00; $p>0.05$]; 3/5-syllable nouns span [Mann-Whitney U-Test = 47.50; $p>0.05$]; and 3/5-syllable proper names span [Mann-Whitney U-Test = 65.00; $p>0.05$]

span, and 2-syllabe proper names span). The results show a significant difference between tasks [$\chi^2(2) = 40.05$, $p<0.001$]. Analyzing these differences further with the Wilcoxon Signed Ranks Test, it emerges that the significant differences are due to the digit span being larger than both the 2-syllable nouns span [$Z = -4.55$, $p<0.001$] and the 2-syllable proper names span [$Z = -4.70$, $p<0.001$], whereas the latter two do not differ significantly[103], as illustrated in Figure 4.2.

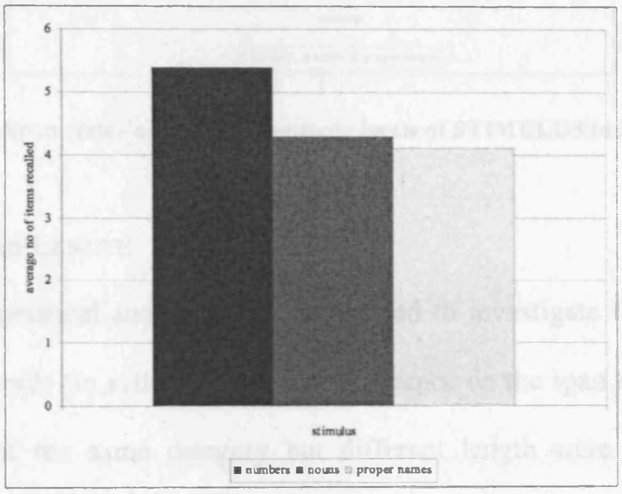

Figure 4. 2: Span tests - comparison between levels of STIMULUS in 2-syll span

Another Friedman Test was performed comparing the performance on the span tests involving three to five-syllable items (i.e. 2-digit span, 3/5-syllable nouns span, and 3/5-syllabe proper names span). The results show a significant difference between tasks [$\chi^2(2) = 22.81$, $p<0.001$]. The Wilcoxon Signed Ranks Test, shows that the significant differences are due to the 2-digit span being smaller than both the 3/5-syllable nouns span [$Z = -3.74$, $p<0.001$] and the 3/5-syllable proper names span [$Z = -3.96$, $p<0.001$], whereas the latter two do not differ significantly[104]. This is illustrated in figure 4.3.

[103] [$Z = -1.41$, $p>0.05$]
[104] [$Z = -0.73$, $p>0.05$]

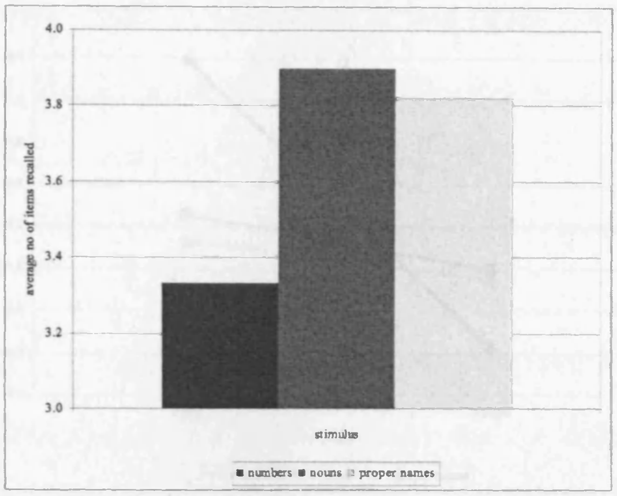

Figure 4. 3: Span tests - comparison between levels of STIMULUS in 3/5-syll span

THE EFFECT OF LENGTH

Other statistical analyses were performed to investigate the effect of the length of the words (in syllable) on the performance on the span test. In order to do so, items of the same category but different length were compared to a Wilcoxon Signed Ranks Test. As illustrated in Figure 4.4, fewer items are recalled for each category when the items to recall are longer (digit span forward vs. 2-digit span [Z= -5.44; p<0.001]; 2-syllables common nouns span vs. 3/5-syllables common nouns span [Z= -2.98; p<0.005]; 2-syllables proper names span vs. 3/5-syllables proper names span [Z= -2.15; p<0.05]).

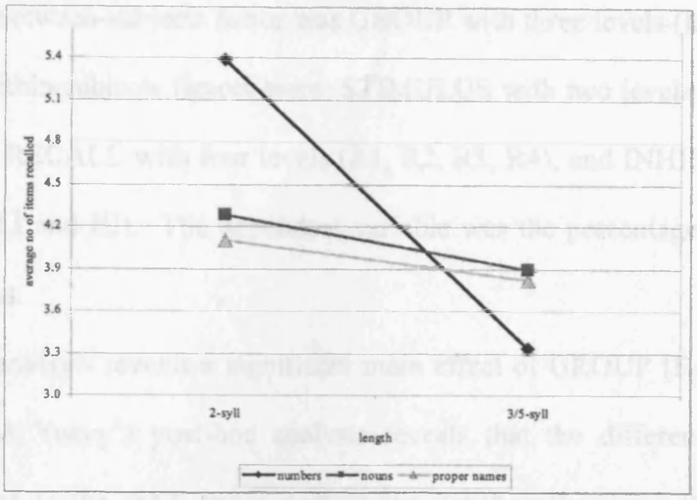

Figure 4. 4: Span tests - comparison between levels of LENGTH with different stimuli

4.3.1.2. Updating Task

In the Updating task, the group of DAT patients, the group of elderly controls (EC), and the group of adult controls (AC) were compared.

Separate analysis were performed in order to investigate the performance of recall (measured as the percentage of correct recall), the production of errors of intrusion of items from the same list, the production of errors of intrusion of items presented in a previous list, the production of items invented by the participant, and the omissions. Errors were measured as the percentage of items incorrectly recalled (or omitted) in place of correct items.

Bonferroni correction was used when multiple comparisons were performed on the data, and all the significance values reported include this correction where necessary.

CORRECT RECALL

A 3x2x4x2 mixed design ANOVA was conducted to see differences in recall performance between the DAT, EC and AC group across conditions.

The between-subjects factor was GROUP with three levels (DAT, EC and AC). The within-subjects factors were: STIMULUS with two levels (NOUN and NUMBER), RECALL with four levels (R1, R2, R3, R4), and INHIBITION with two levels (LI and HI). The dependent variable was the percentage of correctly recalled items.

The analysis reveals a significant main effect of GROUP [$F_{(2,41)} = 19.84$, $p<0.001$]. A Tukey's post-hoc analysis reveals that the differences between groups is due to the DAT group performing significantly worse than both EC [$p<0.002$] and AC [$p<0.001$]. The two control groups instead do not differ one from the other [$p>0.05$]. This can be observed in Figure 4.5.

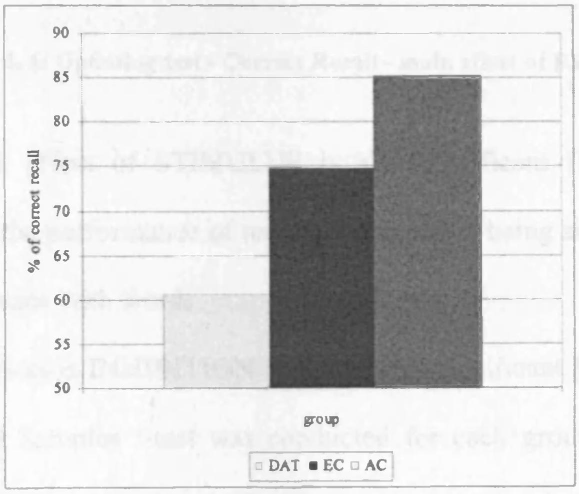

Figure 4. 5: Updating task - Correct Recall - main effect of GROUP

The main effect of INHIBITION is significant [$F(1,41) = 66.02$, $p<0.001$], due to a worse performance on recall when the load on control processes is higher (HI) compared to when the load on control processes is lower LI).

RECALL is a significant main effect [$F(2,101) = 185.74$, $p<0.001$]. As illustrated in Figure 4.6, a polynomial contrast confirms that this factor shows a significantly linear decrease [F(1,41) = 347.52; p<0.001][105]: the percentage of correct recall decreases proportionately to the increase in the number of items to recall.

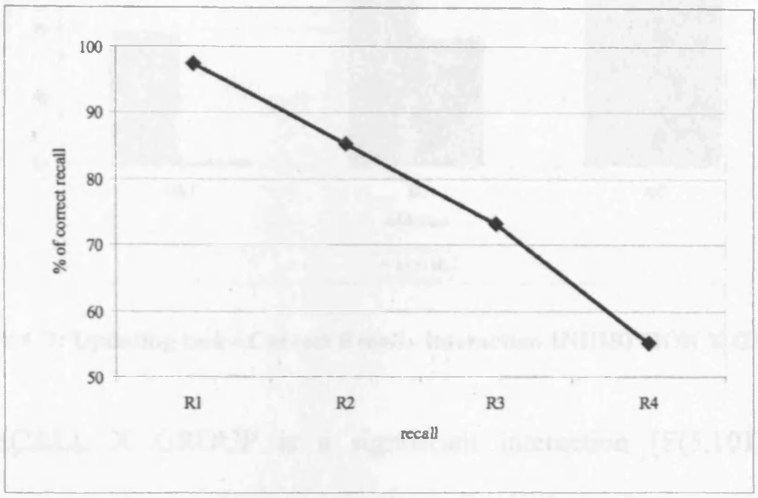

Figure 4. 6: Updating test - Correct Recall - main effect of RECALL

The main effect of STIMULUS is also significant [F(1,41) = 31.56, p<0.001], due to the performance of recall with numbers being significantly worse than the performance with words

The interaction INHIBITION X GROUP is significant [F(2,41) = 5.54, p < 0.01] a Paired Samples t-test was conducted for each group, comparing the performance of recall with LI and HI. The two conditions significantly differ in all groups (DAT [t(18)= 7.80, p<0.005], EC [t(14)= 4.69, p<0.005], AC[t(9)= 7.13, p<0.005]), as shown in Figure 4.7.

[105] No other significant trends were observed.

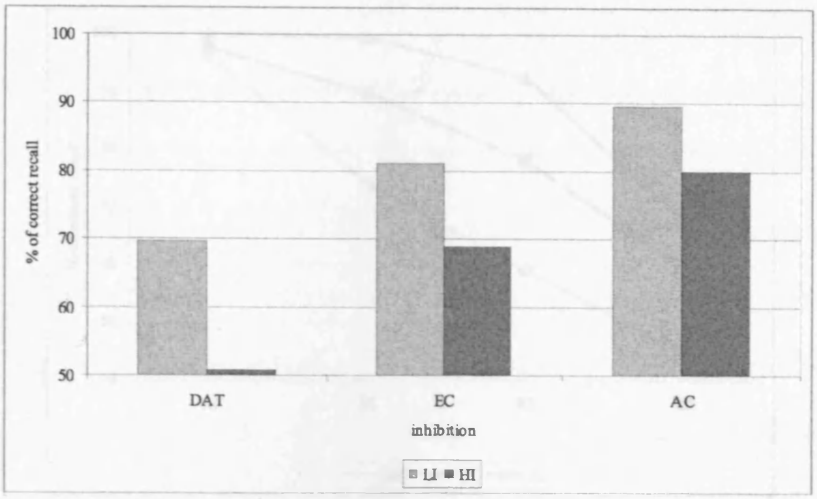

Figure 4. 7: Updating task - Correct Recall - interaction INHIBITION X GROUP

RECALL X GROUP is a significant interaction [$F(5,101) = 8.57$, $p<0.001$]. A between-subjects ANOVA was performed for each level of RECALL, in order to investigate the interaction. This shows that when there is only one item to recall there is no difference between groups[106]. When the items to recall are more than one, groups are significantly different (with R2 [$F(2,41)= 11.02$; $p<0.001$]; R3 [$F(2,41)= 6.56$; $p<0.005$]; and R4 [$F(2,41)= 4.25$; $p<0.05$]). A Tukey's post-hoc test shows that, as illustrated in Figure 4.8, these significant differences are due to the DAT group performing significantly worse than the other two groups, whereas the two control groups do not significantly differ one from the other at any level of RECALL.

[106] [$F(2,41)= 0.21$; $p>0.05$]

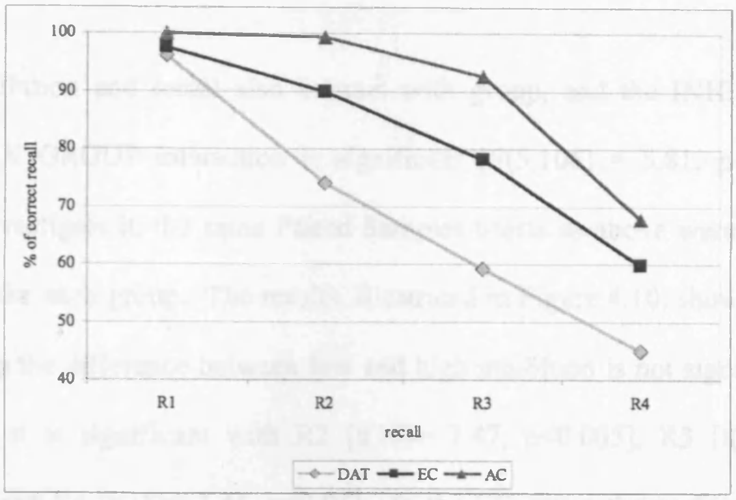

Figure 4. 8: Updating task - Correct Recall -interaction RECALL X GROUP

The INHIBITION X RECALL interaction is significant [$F(3,106) = 11.08$, $p<0.001$]. A Paired Samples t-test was conducted for each level of RECALL, comparing the performance with low versus high inhibition. As illustrated in Figure 4.9, this shows that the difference between the two conditions of inhibition is not significant when the task requires to recall only one item[107], but it is significant at each of the other three levels: with R2 [$t(43)= 4.75$, $p<0.005$], R3 [$t(43)= 7.97$, $p<0.005$], and R4 [$t(43)= 6.34$, $p<0.005$].

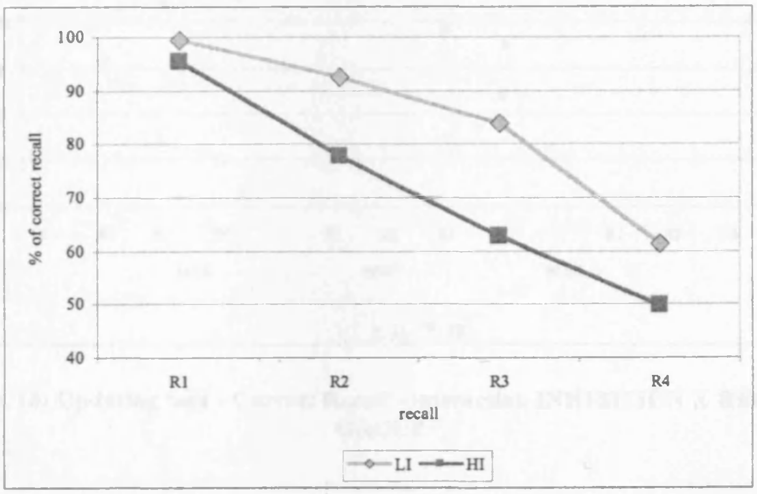

Figure 4. 9: Updating task - Correct Recall - interaction INHIBITION X RECALL

[107] R1: [$t(43)= 2.30$, $p>0.05$]

Inhibition and recall also interact with group, and the INHIBITION X RECALL X GROUP interaction is significant [F(5,106) = 5.81, p<0.001]. In order to investigate it, the same Paired Samples t-tests as above were performed separately for each group. The results, illustrated in Figure 4.10, show that in the DAT group the difference between low and high inhibition is not significant with R1[108], but it is significant with R2 [t(18)= 7.47, p<0.005], R3 [t(18)= 6.57, p<0.005], and R4 [t(18)= 3.41, p<0.05]. In the EC group the performance with high inhibition is worse than the performance with low inhibition when the task requires recalling three [t(14)= 6.45, p<0.005] and four items [t(14)= 3.47, p<0.05], but there is no difference between levels of inhibition when the items to recall are only one or two[109]. Lastly, the AC group shows a significant difference between levels of inhibition only with four items to recall [t(9)= 4.61, p<0.01], and no difference at the other levels of recall[110].

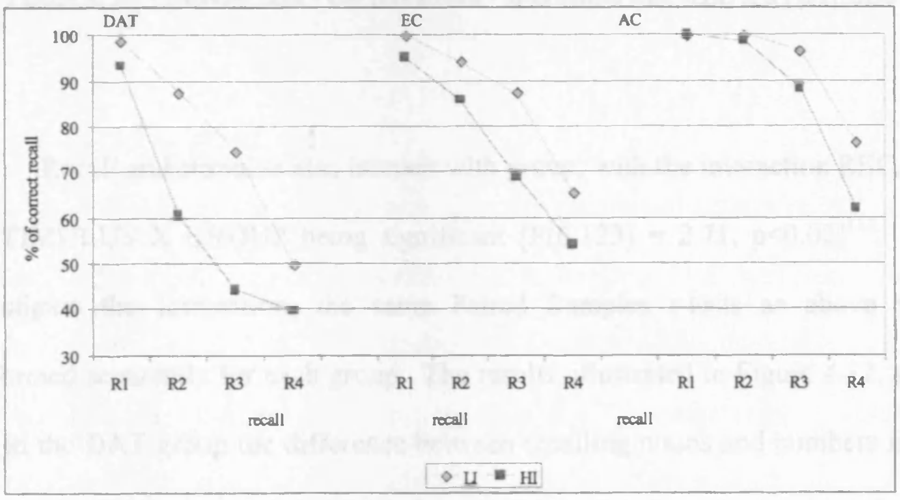

Figure 4. 10: Updating task - Correct Recall - interaction INHIBITION X RECALL X GROUP

108 [t(18)= 2.19, p>0.05]
109 R1: [t(14)= 1.38, p>0.05]; R2: [t(14)= 1.38, p>0.05]
110 R1 [t(9)= 1.00, p>0.05]; R2 [t(9)= 1.13, p>0.05]; and R3 [t(9)= 2.37, p>0.05]

The interaction RECALL X STIMULUS is significant [F(3,123) = 14.07, p<0.001]. A Paired Samples t-test was conducted for each level of RECALL, comparing the performance at the different levels of STIMULUS (NOUN and NUMBER). Figure 4.11 shows that the difference between the two levels of stimulus is only significant when the task requires to recall four items (R4) [t(43)= 7.09, p<0.005], and it is not significant at the other levels[111].

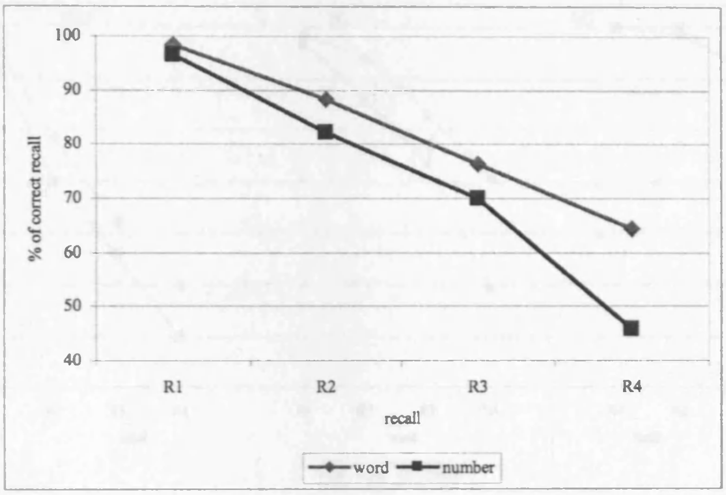

Figure 4. 11: Updating task - Correct Recall - interaction RECALL X STIMULUS

Recall and stimulus also interact with group, with the interaction RECALL X STIMULUS X GROUP being significant [F(6,123) = 2.71, p<0.02][112]. To investigate the interaction, the same Paired Samples t-tests as above were performed separately for each group. The results, illustrated in Figure 4.12, show that in the DAT group the difference between recalling nouns and numbers is not

[111] R1 [t(43)= 1.00, p>0.05], R2 [t(43)= 2.39, p>0.05], and R3 [t(43)= 2.52, p>0.05]

[112] The other interactions (STIMULUS X GROUP [F(2,41) = 0.61, p>0.05], INHIBITION X STIMULUS [F(1,41) = 0.26, p>0.05]; INHIBITION X STIMULUS X GROUP [F(2,41) = 0.18, p>0.05]; INHIBITION X RECALL X STIMULUS [F(2,98) = 0.05, p>0.05]; and INHIBITION X RECALL X STIMULUS X GROUP [F(5,98) = 0.27, p>0.05]) were not significant.

significant at any of the levels of recall[113]. In the EC group, performance of recall with numbers is worse than performance with nouns only when the task requires recalling four items (R4) [$t(14)= 7.14$, $p<0.005$][114]. The AC group shows the same pattern as the EC group: a significant difference between levels of STIMULUS only with four items to recall [$t(9)= 5.44$, $p<0.005$], and no difference with the other conditions of recall[115].

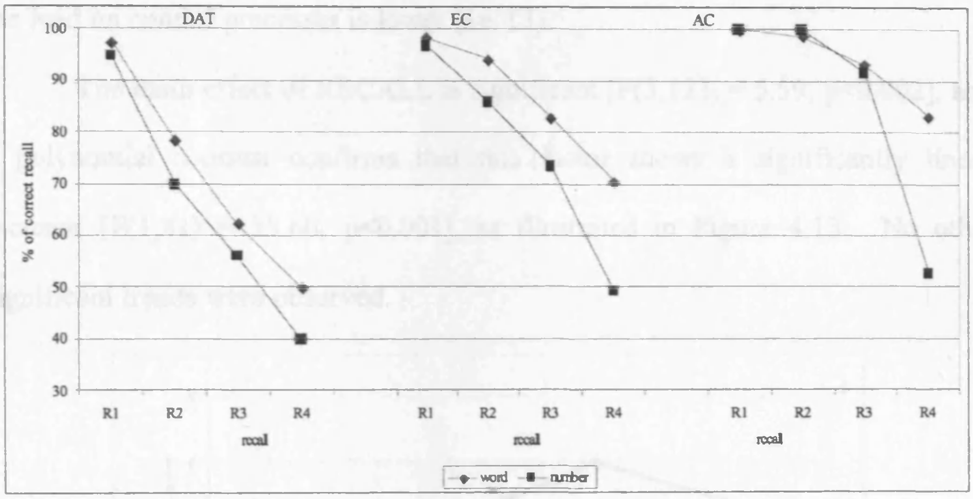

Figure 4. 12: Updating task - Correct Recall - interaction RECALL X STIMULUS X GROUP

SAME LIST INTRUSION ERRORS

A 3x2x4x2 mixed design ANOVA was conducted to assess differences between the three groups across conditions in the production of intrusion errors of words from the same list. The independent variables were the same as in the previous analysis, and the dependent variable was the percentage of intrusions from the same list (as a proportion of the total number of responses).

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113 R1 [$t(18)= 0.70$, $p>0.05$], R2 [$t(18)= 1.58$, $p>0.05$], R3 [$t(18)= 1.37$, $p>0.05$], and R4 [$t(18)= 2.49$, $p>0.05$]

114 there was no difference between levels of STIMULUS with R1 [$t(14)= 1.00$, $p>0.05$], R2 [$t(14)= 2.65$, $p>0.05$], and R3 [$t(14)= 2.83$, $p>0.05$]

115 R1 [n.s.: Could not compute the difference since all scores were equivalent]; R2 [$t(9)= -1.00$, $p>0.05$]; and R3 [$t(9)= 0.35$, $p>0.05$]

The main effect of GROUP is significant [F(2,41) = 3.71, p<0.05], but the difference between groups disappears when a Tukey's post-hoc analysis is conducted. None of the three groups does significantly differ from the other.

The analysis also reveals a significant main effect of INHIBITION [F(1,41) = 29.28, p<0.001], explained by a higher percentage of intrusions from the same list, when the load on control processes is higher (HI) compared to when the load on control processes is lower (i.e. LI).

The main effect of RECALL is significant [F(3,123) = 5.59, p<0.002], and a polynomial contrast confirms that this factor shows a significantly linear increase [F(1,41) = 15.60; p<0.001], as illustrated in Figure 4.13. No other significant trends were observed.

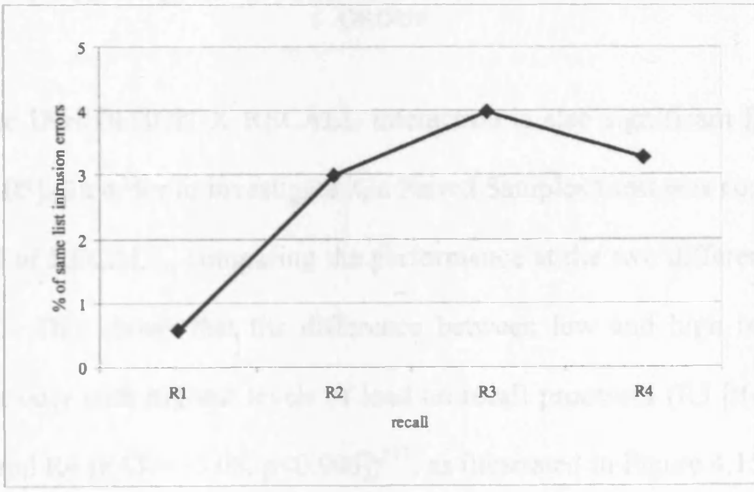

Figure 4. 13: Updating task - Same list intrusion errors - main effect of RECALL

STIMULUS is also a significant main effect [F(1,41) = 11.29, p<0.005], due to a higher percentage of intrusions from the same list errors being produced with words than with numbers.

The interaction INHIBITION X GROUP is significant [F(2,41) = 3.50, p<0.05], and it was further analysed by conducting a Paired Samples t-test in each group, comparing the performance of recall with low and high inhibition. Figure 4.14 illustrates that the two conditions significantly differ in the DAT group [t(18)= -4.43, p<0.005], but they do not differ in the other two groups[116].

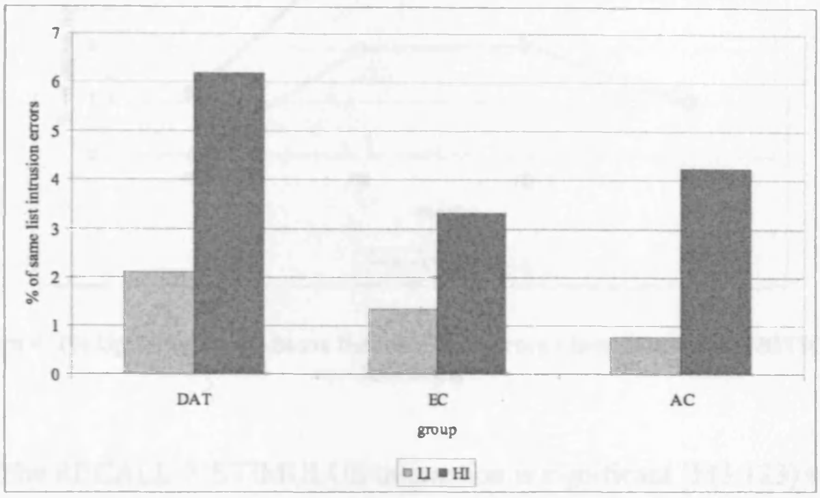

Figure 4. 14: Updating task - Same list intrusion errors - interaction INHIBITION X GROUP

The INHIBITION X RECALL interaction is also significant [F(3,123) = 3.15, p<0.05]. In order to investigate it, a Paired Samples t-test was conducted for each level of RECALL, comparing the performance at the two different levels of inhibition. This shows that the difference between low and high inhibition is significant only with highest levels of load on recall processes (R3 [t(43)= -3.74, p<0.01]; and R4 [t(43)= -5.08, p<0.005])[117], as illustrated in Figure 4.15.

[116] when the Bonferroni correction was applied: EC [t(14)= -2.70, p>0.05]; AC[t(9)= -2.91, p>0.05]

[117] The difference between HI and LI was not significant when the task required to recall one item (R1) [t(43)= -1.43, p>0.05] or two items (R2) [t(43)= -1.64, p>0.05].

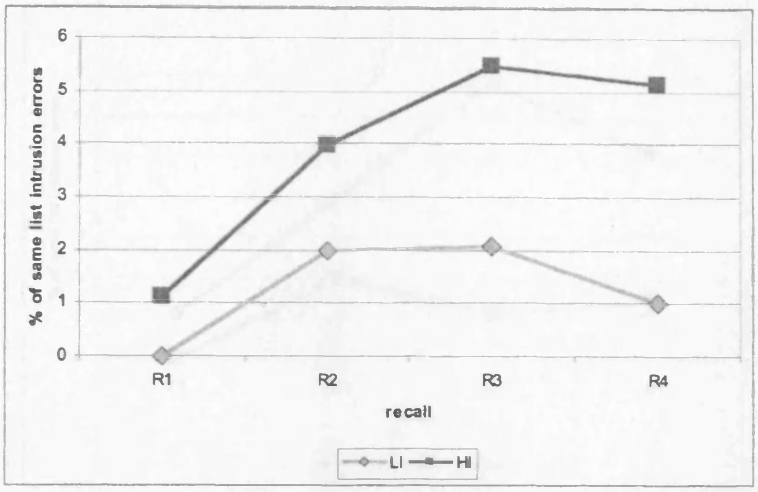

Figure 4. 15: Updating task - Same list intrusion errors - interaction INHIBITION X RECALL

The RECALL X STIMULUS interaction is significant [$F(3,123) = 3.03$, $p < 0.05$][118]. A Paired Samples t-test was conducted for each level of RECALL, comparing the performance at the different levels of stimulus. As illustrated in Figure 4.16, the difference between nouns and numbers are only significant when the task requires to recall three (R3) [$t(43)= 3.91$, $p<0.005$] or four items (R4) [$t(43)= 3.69$ $p<0.01$][119].

[118] The other interactions (RECALL X GROUP [$F(6,123) = 1.80$, $p>0.05$], STIMULUS X GROUP [$F(2,41) = 1.53$, $p>0.05$], INHIBITION X RECALL X GROUP [$F(6,123) = 0.89$, $p>0.05$], INHIBITION X STIMULUS X GROUP [$F(2,41) = 0.19$, $p>0.05$]; RECALL X STIMULUS X GROUP [$F(6,123) = 1.47$, $p>0.05$], INHIBITION X RECALL X STIMULUS [$F(2,100) = 0.46$, $p>0.05$]; and INHIBITION X RECALL X STIMULUS X GROUP [$F(5,100) = 0.67$, $p>0.05$]) were not significant.

[119] The difference was not significant at the other levels (R1 [$t(43)= 1.00$, $p>0.05$], and R2 [$t(43)= 2.39$, $p>0.05$])

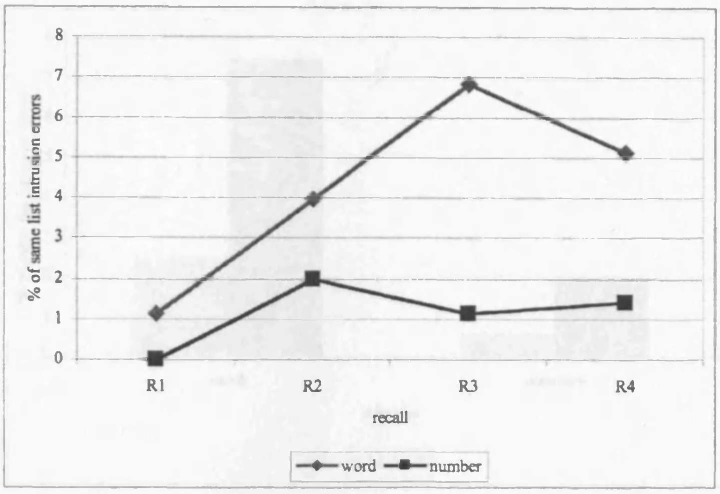

Figure 4. 16: Updating task - Same list intrusion errors - interaction RECALL X STIMULUS

Inhibition also interacts with stimulus: the interaction INHIBITION X STIMULUS is significant [F(1,41) = 6.93, p<0.05], and it was analyzed conducting a Paired Sample t-test for each level of stimulus comparing the percentage of intrusion errors from the same list at the different levels of INHIBITION (LI and HI). The results show that with both stimuli the difference between conditions of INHIBITION is significant, but the effect appears to be bigger for words [t(43)= -5.76, p<.005] than for numbers [t(43)= -2.39, p<.05], as shown in Figure 4.17.

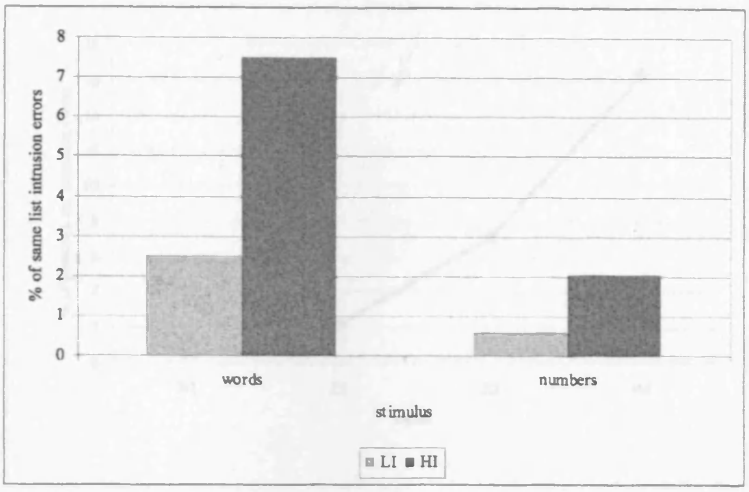

Figure 4. 17: Updating task - Same list intrusion errors - interaction INHIBITION X STIMULUS

PREVIOUS LIST INTRUSION ERRORS

A 3x2x4x2 mixed design ANOVA was conducted to see differences between the three groups across conditions in the production of intrusion errors of words from a list previously presented. The independent variables were the same as in the previous analysis. The dependent variable was the percentage of intrusions from a previous list (as a proportion of the total number of responses).

The main effect of INHIBITION is significant [$F(1,41) = 18.42$, $p<0.001$], explained by a higher percentage of intrusions from the previous list, when the load on control processes is high.

RECALL is a significant main effect [$F(2,71) = 88.81$, $p<0.001$], and a Polynomial contrast between the levels of RECALL shows that this variable is better accounted for by a quadratic[120] decrease [$F(1,41) = 52.26$; $p<.0.001$], as illustrated in Figure 4.18.

[120] A linear increase was also found to be significant [$F(1,41) = 124.74$; $p<.0.001$].

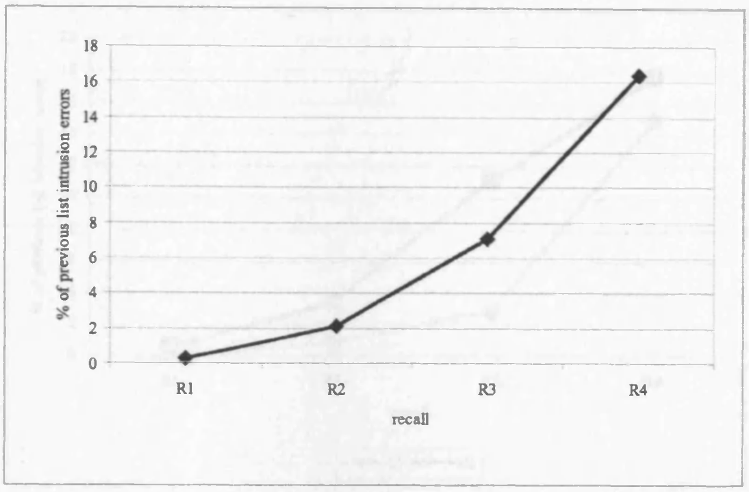

Figure 4.18: Updating task - Previous list intrusion errors - main effect of RECALL

The main effect of STIMULUS is also significant [F(1,41) = 91.89, p<0.001], due to a higher percentage of intrusions from the previous list errors being produced with numbers than with words.

The analysis revealed no significant main effect of GROUP[121].

The interaction INHIBITION X RECALL is significant [F(2,95) = 6.55, p < 0.001]. A Paired Samples t-test was conducted for each level of RECALL, comparing the performance at the two different levels of INHIBITION. Figure 4.19 shows that the difference between conditions with low and high load on inhibition (i.e. LI and HI) is only significant with R2 [t(43)= -2.45, p<.05], and R3 [t(43)= -6.28, p<.005][122].

[121] [F(2,41) = 2.47, p>0.05]

[122] The difference was not significant when the task required to recall one item (R1) [t(43)= -1.00, p>0.05] or four items (R4) [t(43)= -1.71, p>0.05].

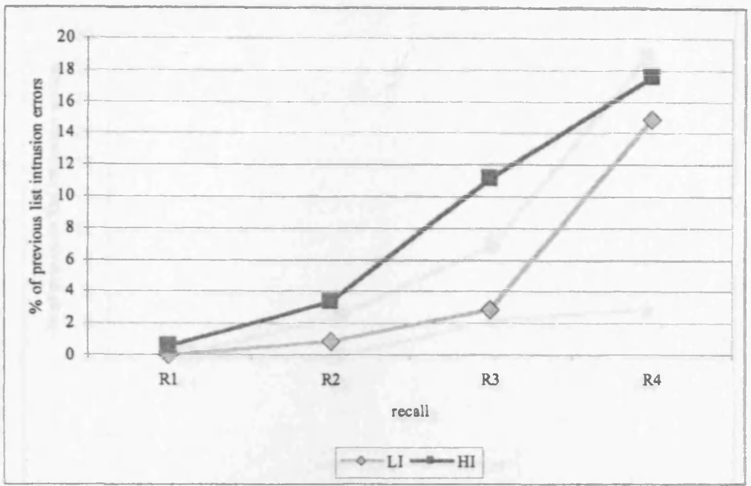

Figure 4. 19: Updating task - Previous list intrusion errors - interaction INHIBITION X RECALL

RECALL X STIMULUS is a significant interaction [$F(2,92) = 64.08$, $p < 0.001$], and a Paired Samples t-test was conducted for each level of RECALL, comparing the percentage of errors from a previous list at the different levels of stimulus. Figure 4.20 illustrates that the difference between nouns and numbers is significant when the task requires to recall two, three or four items (R2 [$t(43)= -3.85$, $p <0.005$], R3 [$t(43)= -4.00$, $p<0.005$] and R4 [$t(43)= -11.65$; $p<0.005$])[123].

[123] The difference is not significant in the condition with only one item to recall (R1) [$t(43)= -1.00$, $p>0.05$].

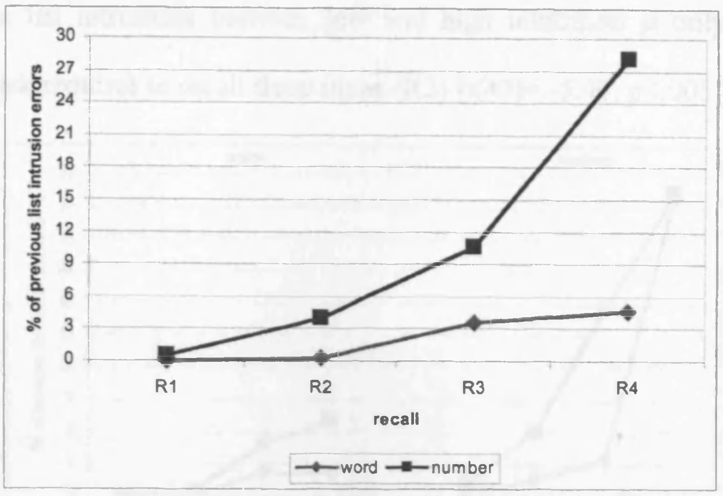

Figure 4. 20: Updating task - Previous list intrusion errors - interaction RECALL X STIMULUS

Recall and stimulus also interact with inhibition, and the INHIBITION X RECALL X STIMULUS is significant [$F(2,91) = 6.86$, $p < 0.002$][124]. This interaction was investigated performing two separate Paired Samples t-tests, one for each level of stimulus. In each t-test the percentage of intrusion errors from a previous list in the condition of low inhibition was compared to the percentage of the same type of errors in the condition of high inhibition, at each level of recall. The results, illustrated in Figure 4.21, show that when the stimuli to be recalled are words, the difference in the percentage of previous list intrusions between LI and HI is only significant when the task requires to recall four items (R4) [$t(43)= -3.27$, $p<.02$][125]. With numbers to recall, instead, the difference in the percentage

[124] Moreover, the same factors interacted with group: INHIBITION X RECALL X STIMULUS X GROUP was a significant interaction [$F(4,91) = 2.83$, $p<0.05$].The other interactions (INHIBITION X GROUP [$F(2,41) = 2.21$, $p>0.05$], RECALL X GROUP [$F(3,71) = 1.91$, $p>0.05$], STIMULUS X GROUP [$F(2,41) = 1.64$, $p>0.05$], INHIBITION X RECALL X GROUP [$F(5,95) = 1.86$, $p>0.05$], INHIBITION X STIMULUS [$F(1,41) = 3.21$, $p>0.05$], INHIBITION X STIMULUS X GROUP [$F(2,41) = 1.61$, $p>0.05$]; RECALL X STIMULUS X GROUP [$F(4,92) = 2.37$, $p>0.05$],) were not significant.

[125] The difference was not significant with R1 [n.s.: Could not compute the difference since all scores were equivalent], R2 [$t(43)= -1.00$, $p>0.05$], and R3 [$t(43)= -1.86$, $p>0.05$]

of previous list intrusions between low and high inhibition is only significant when the task requires to recall three items (R3) [t(43)= -5.40, p<.005][126].

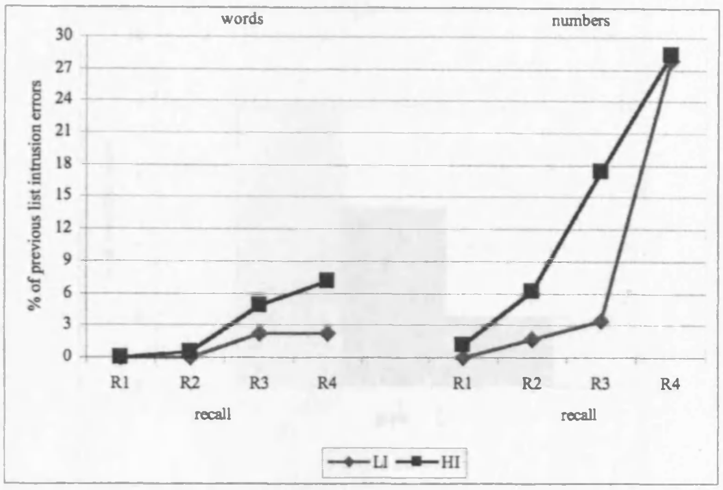

Figure 4. 21: Updating task - Previous list intrusion errors - interaction INHIBITION X RECALL X STIMULUS

INVENTION ERRORS

A 3x2x4x2 mixed design ANOVA was conducted to see differences between the three groups across conditions in the production of invention errors (i.e. the production of false recall: the recall of words or numbers that had not been presented neither in the current list nor in a previous one). The independent variables were the same as in the previous analysis, and the dependent variable was the percentage of invention errors (as a proportion of the total number of responses).

The analysis reveals a significant main effect of GROUP [F(2,41) = 8.10, p<0.002]. A Tukey's post-hoc analysis reveals that the differences between groups is due to the DAT group performing significantly worse than both EC

[126] The difference was not significant with R1 [t(43)= -1.00, p>0.05], R2 [t(43)= -2.23, p>0.05], and R4 [t(43)= -0.21, p>0.05]

[p<0.05] and AC [p<0.002], as illustrated in Figure 4.22. The two control groups instead do not differ from one another [p>0.05].

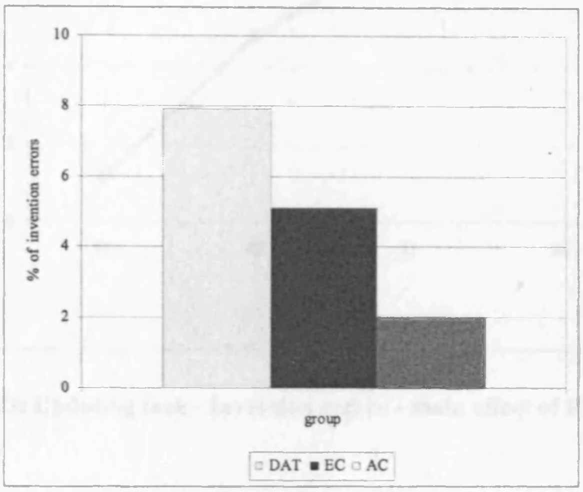

Figure 4. 22: Updating task - Invention errors - main effect of GROUP

The main effect of INHIBITION is significant [$F(1,41) = 4.45$, $p<0.05$], and it is explained by a higher percentage of inventions when the load on control processes is high.

The main effect of RECALL is significant [$F(3,123) = 10.07$, $p<0.001$]. A Polynomial contrast between the levels of this variable shows that it is better accounted for by a quadratic[127] increase [$F(1,41) = 5.75$; $p<.0.05$], as shown in Figure 4.23.

[127] A linear increase was also found to be significant [$F(1,41) = 24.84$; $p<.0.001$].

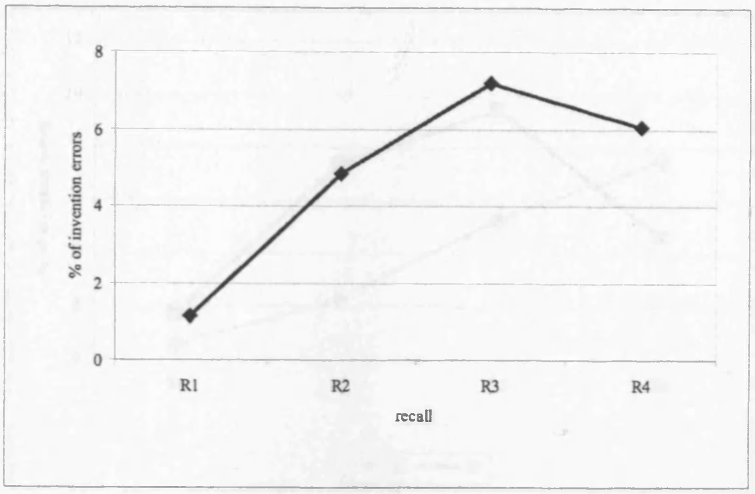

Figure 4. 23: Updating task - Invention errors - main effect of STIMULUS

STIMULUS is also a significant main effect [$F(1,41) = 31.85$, $p<0.001$], due to a higher percentage of invention errors being produced with numbers than with words.

The interaction INHIBITION X RECALL is significant [$F(2,101) = 4.77$, $p < 0.01$] In order to investigate it, a Paired Samples t-test was conducted for each level of RECALL, comparing the performance on the different levels of inhibition. As illustrated in Figure 4.24, the difference between low and high inhibition is only significant when the task requires to recall two items (R2) [$t(43)= -3.22$, $p<.02$][128].

[128] The difference is not significant when the condition of recall is R1 [$t(43)= -1.43$, $p>0.05$], R3 [$t(43)= -2.51$, $p>0.05$], or R4 [$t(43)= 1.78$, $p>0.05$]

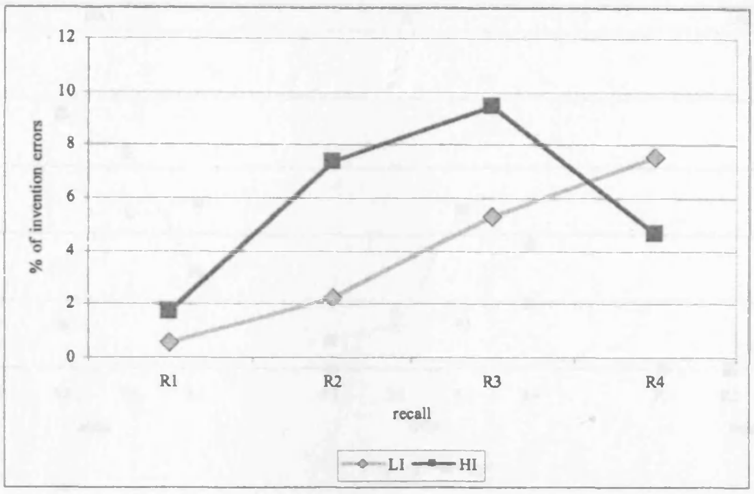

Figure 4. 24: Updating task - Invention errors - interaction INHIBITION X RECALL

Inhibition and recall also interact with group: the INHIBITION X RECALL X GROUP interaction is significant [F(5,101) = 4.67, p<0.002.]. This was analyzed performing the same analysis as above in the separate groups. Figure 4.25 illustrates that in the DAT group the pattern of production of invention errors is the same described above (i.e. the difference between low and high inhibition is only significant with R2 [t(18)= -4.62, p<.005][129]. In the EC group the production of inventions with low and high inhibition is significantly different only with R3 [t(14)= -4.62, p<.05][130]. In the AC group no difference was found between LI and HI at any level of RECALL[131].

[129] The difference is not significant with R1 [t(18)= -1.00, p>0.05], R3 [t(18)= -1.05, p>0.05], or R4 [t(18)= 1.58, p>0.05].
[130] The difference is not significant with R1 [t(14)= -1.00, p>0.05], R2 [t(14)= 0.56, p>0.05], or R4 [t(18)= 1.50, p>0.05].
[131] (R1, R2 [for both conditions n.s.], R3 [t(9)= -1.00, p>0.05], and R4 [t(9)= -1.15, p>0.05])

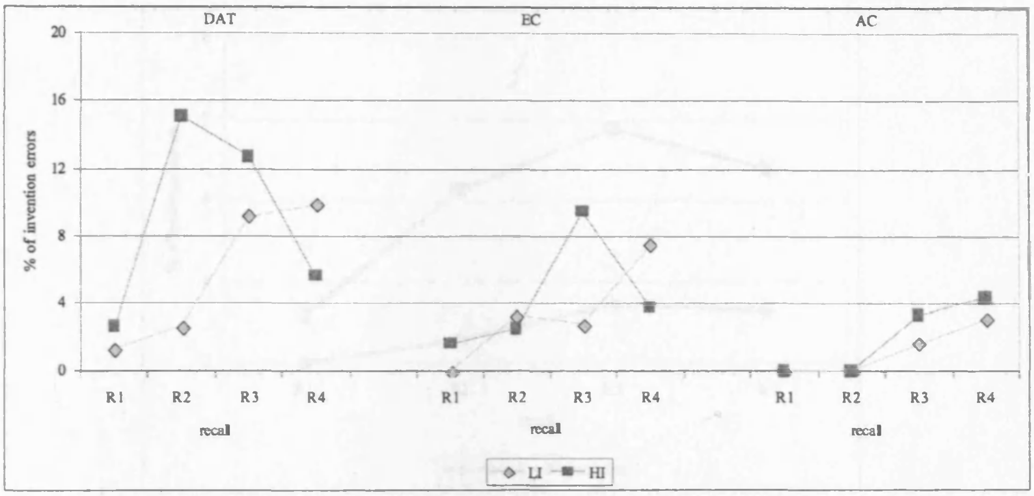

Figure 4. 25: Updating task - Invention errors - interaction INHIBITION X RECALL X GROUP

The interaction RECALL X STIMULUS is significant [$F(2,102) = 3.21$, $p < 0.05$]. A Paired Samples t-test was conducted for each level of RECALL, comparing the percentage of errors of invention at the different levels of stimulus. Figure 4.26 shows that the difference between nouns and numbers is not significant when the task requires to recall only one item[132], and it is significant at all other levels (R2 [$t(43)= -4.64$, $p <0.005$], R3 [$t(43)= -3.96$, $p<0.005$] and R4 [$t(43)= -5.77$; $p<0.005$]).

[132] (R1) [$t(43)= -1.67$, $p>0.05$]

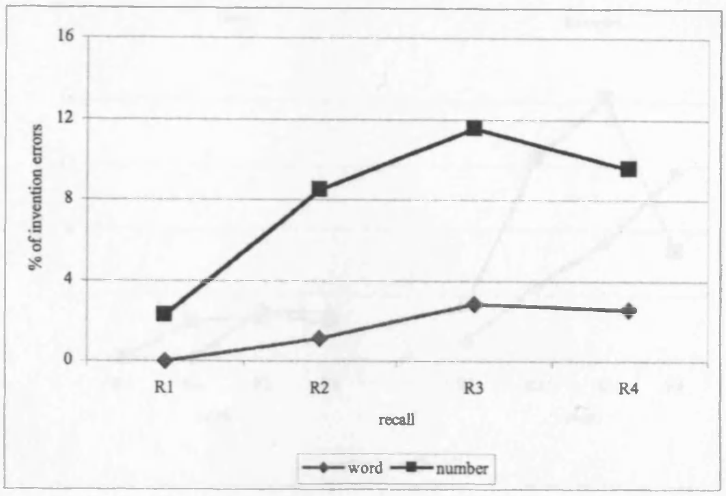

Figure 4. 26: Updating task - Invention errors - interaction RECALL X STIMULUS

Recall and stimulus also interact with inhibition, as the INHIBITION X RECALL X STIMULUS interaction is significant [F(2,100) = 3.94, p <0.02][133]. This interaction was investigated performing two separate Paired Samples t-tests, one for each level of STIMULUS. In each t-test the percentage of inventions produced in the condition of low inhibition was compared to the percentage of the same type of errors in the condition of high inhibition, at each level of recall. The results, illustrated in Figure 4.27, show that when the stimuli to be recalled are words, there is no significant difference between LI and HI[134]. With numbers to recall, instead, the difference in the percentage of inventions between LI and HI is significant when the task requires to recall two (R2) [t(43)= -2.74, p<.05],and three items (R3) [t(43)= -2.95, p<.05], but not one (R1) [t(43)= -1.43, p>0.05], and four (R4) [t(43)= 1.85, p>0.05].

[133] The other interactions (INHIBITION X GROUP [F(2,41) = 1.78, p>0.05], RECALL X GROUP [F(6,123) = 1.74, p>0.05], STIMULUS X GROUP [F(2,41) = 3.10, p>0.05], INHIBITION X STIMULUS [F(1,41) = 3.04, p>0.05], INHIBITION X STIMULUS X GROUP [F(2,41) = 0.11, p>0.05]; RECALL X STIMULUS X GROUP [F(5,102) = 1.40, p>0.05],), and INHIBITION X RECALL X STIMULUS X GROUP [F(5,100) = 2.19, p>0.05] were not significant.

[134] (R1 [n.s.: Could not compute the difference since all scores were equivalent], R2 [t(43)= -1.67, p>0.05], and R3 [t(43)= 0.23, p>0.05], R4 [t(43)= 0.63, p>0.05]

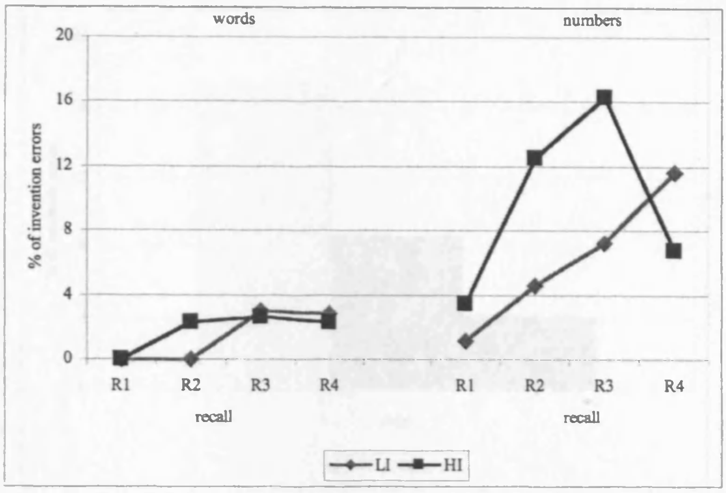

Figure 4. 27: Updating task - Invention errors - interaction INHIBITION X RECALL X STIMULUS

OMISSION ERRORS

A 3x2x4x2 mixed design ANOVA was conducted to see differences between the three groups across conditions in the percentage of omissions (i.e., out of the total of items that the participant was asked to recall, the percentage of items not recalled at all). The independent variables were the same as in the previous analysis, while the dependent variable was the percentage of omissions (as a proportion of the total number of responses).

The analysis reveals a significant main effect of GROUP [$F(2,41) = 10.13$, $p<0.001$]. A Tukey's post-hoc analysis reveals that the differences between groups is due to the DAT group performing significantly worse than both the EC [$p<0.02$] and the AC [$p<0.001$][135] group, as illustrated in Figure 4.28.

[135] The two control groups did not differ one from the other [$p>0.05$].

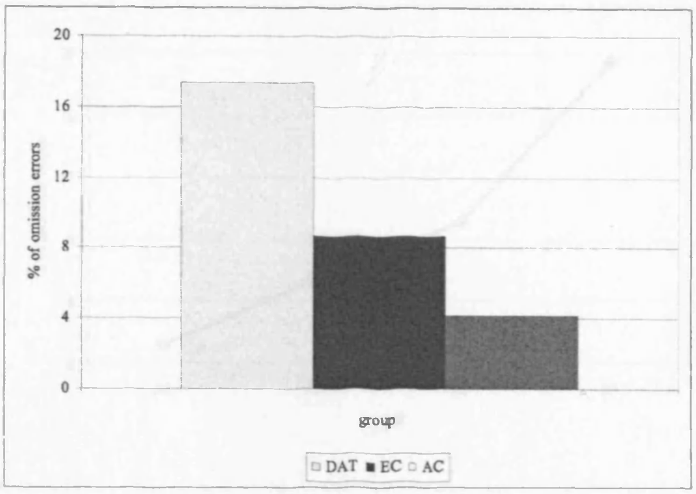

Figure 4. 28: Updating task - Omission errors - main effect of GROUP

The main effect of INHIBITION is significant [$F(1,41) = 21.58$, $p<0.001$], and it is explained by a higher percentage of omissions when the load on control processes is high.

The main effect of RECALL is significant [$F(3,123) = 43.40$, $p<0.001$]. A Polynomial contrast between the levels of RECALL show that this variable is better accounted for by a linear[136] increase [$F(1,41) = 94.27$; $p<.0.001$]. This can be observed in Figure 4.29 where the percentage of omission errors increases proportionately to the increase in the number of items to recall.

[136] A quadratic increase was also found to be significant [$F(1,41) = 10.48$; $p<.0.005$].

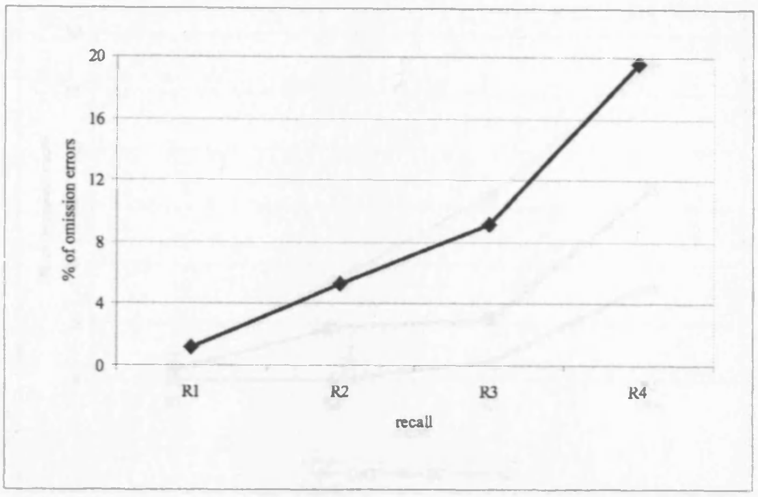

Figure 4. 29: Updating task - Omission errors - main effect of RECALL

STIMULUS is a significant main effect [$F(1,41) = 5.15$, $p<0.05$], due to a higher percentage of omissions when the task requires to recall words.

The interactions RECALL X GROUP is significant [$F(6,123) = 4.15$, $p<0.002$]. A between-subjects ANOVA was performed for each level of recall, in order to investigate this interaction. This shows that when there is only one item to recall there is no difference between groups[137]. When the items to recall are more than one, the groups are significantly different (with R2 [$F(2,41)= 3.60$; $p<0.05$], R3 [$F(2,41)= 10.85$; $p<0.001$], and R4 [$F(2,41)= 9.60$; $p<0.001$]). A Tukey's post-hoc test shows that the significant difference with R2 is due to the DAT group performing significantly worse than the AC group ($p<0.05$), but not than the EC group. With R3 and R4 the significant differences were between DAT and EC (with R3 $p<0.005$; with R4 $p<0.05$), and between DAT and AC ($p<0.001$ with both R3 and R4), whereas the two control groups do not significantly differ from one another at any level of recall. This is illustrated in Figure 4.30.

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137 [$F(2,41)= 0.38$; $p>0.05$]

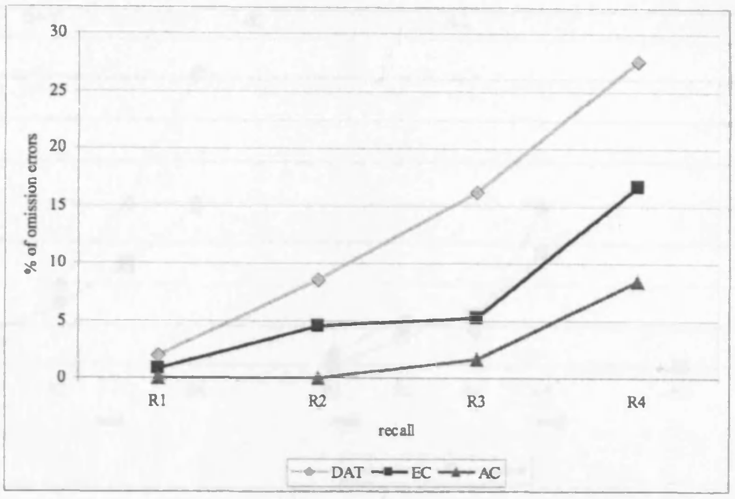

Figure 4. 30: Updating task - Omission errors - interaction RECALL X GROUP

Recall and group also interact with stimulus: the interaction RECALL X STIMULUS X GROUP is in fact significant [F(6,123) = 2.65, p<0.02][138]. In order to analyse this interaction, a separate Paired Samples t-test was conducted in each group comparing, for each level of recall, the percentage of omissions at the different levels of stimulus. Figure 4.31 shows that the difference between nouns and numbers is only significant when the task requires to recall four items (R4), and only in the DAT group [t(18)= 3.87; p<0.01]. In all other conditions of recall and in all groups, the difference in the percentage of omissions is not significant[139].

[138] The other interactions (INHIBITION X GROUP [F(2,41) = 1.40, p>0.05], , STIMULUS X GROUP [F(2,41) = 2.72, p>0.05], INHIBITION X RECALL [F(2,92) = 1.76, p>0.05], INHIBITION X RECALL X GROUP [F(4,92) = 1.31, p>0.05.], INHIBITION X STIMULUS [F(1,41) = 0.01, p>0.05], INHIBITION X STIMULUS X GROUP [F(2,41) = 0.26, p>0.05], RECALL X STIMULUS [F(3,123) = 2.12, p>0.05], INHIBITION X RECALL X STIMULUS [F(3,123) = 1.06, p>0.05], and INHIBITION X RECALL X STIMULUS X GROUP [F(6,123) = 1.65, p>0.05] were not significant.

[139] (with R1: in DAT [t(18)= -1.00, p>0.05],in EC [t(14)= 1.00, p>0.05], in AC this analysis was not computed by SPSS since all scores were equivalent; withR2: in DAT [t(18)= o.89, p>0.05],in EC [t(14)= 0.68, p>0.05], in AC this analysis was not computed by SPSS since all scores were equivalent; with R3: in DAT [t(18)= 1.86, p>0.05],in EC [t(14)= -0.68, p>0.05], in AC [t(9)= 0.80 p>0.05]; with R4: in EC [t(14)= 1.58, p>0.05], in AC [t(9)= -1.96 p>0.05].

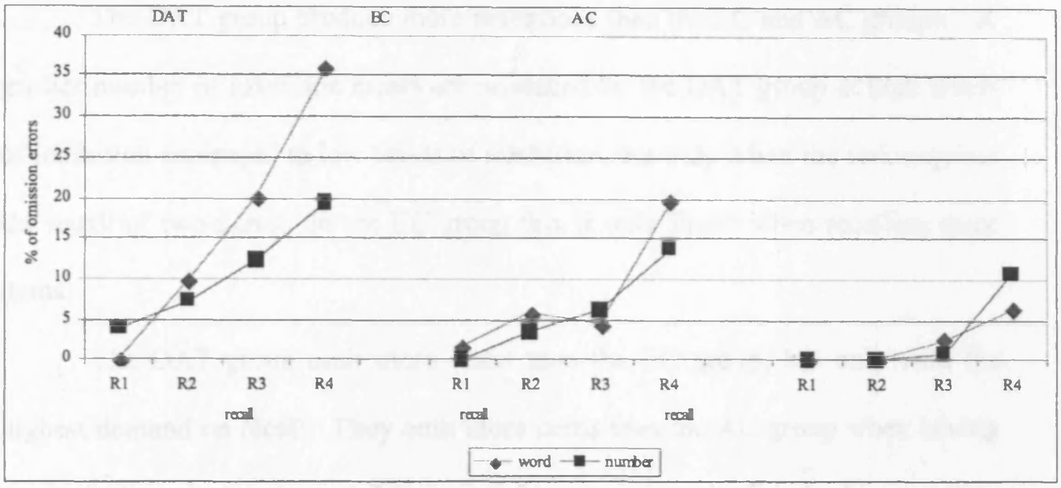

Figure 4. 31: Updating task - Omission errors - interaction RECALL X STIMULUS X GROUP

4.3.1.3. Summary of Updating Results

Table 4.3 illustrates a summary of the group effects of DAT and ageing on the Updating task. Recall performance is significantly worse in the DAT group than in the group of elderly (EC) and adult (AC) controls at higher levels of load on recall. When only one item has to be recalled, the groups perform similarly - at ceiling. While all the groups show better recall performance with a lower load on inhibition processes, in the AC group this is only significant when the demand of the task is to recall four items, in the EC group when recalling three or more items, and in the DAT group it is significant when recalling two or more items. There is no difference between recalling words and numbers, except between the groups of adults and elderly when the demands on recall are highest.

No difference is evident between groups in the production of same list intrusion errors. However, the DAT group produced more same list intrusion errors when the load on inhibition is higher. There is no difference between groups in the production of intrusion errors from a previous list.

The DAT group produce more inventions than the EC and AC groups. A greater number of invention errors are produced by the DAT group at high levels of inhibition compared to low levels of inhibition, but only when the task requires the recall of two items. In the EC group this is only found when recalling three items.

The DAT group omit more items than the EC group, but only with the highest demand on recall. They omit more items than the AC group when having to recall three or four items. More omission errors are produced when recalling nouns than when recalling numbers by the DAT group, but only with the highest demand on recall.

Table 4. 3: Effects of group - summary of results

		RESULTS
RECALL	GROUP	DAT<EC; DAT<AC
	INHIBITION X GROUP	LI>HI in DAT; EC; AC (?)
	RECALL X GROUP	DAT<EC and DAT<AC with R2; R3; R4
	STIMULUS X GROUP	n.s.
	INHIB X REC X GROUP	In DAT LI>HI with R2; R3; R4 In EC LI>HI with R3;R4 In AC LI>HI with R4
	INHIB X STIM X GROUP	n.s.
	REC X STIM X GROUP	In DAT W=N with R1; R2; R3; R4 In EC and AC W>N with R4
	INHIB X REC X STIM X GROUP	n.s.
SAME LIST INTRUSIONS	GROUP	n.s.
	INHIBITION X GROUP	LI>HI only in DAT
	RECALL X GROUP	n.s.
	STIMULUS X GROUP	n.s.
	INHIB X REC X GROUP	n.s.
	INHIB X STIM X GROUP	n.s.
	REC X STIM X GROUP	n.s.
	INHIB X REC X STIM X GROUP	n.s.
PREVIOUS LIST INTRUSIONS	GROUP	n.s.
	INHIBITION X GROUP	n.s.
	RECALL X GROUP	n.s.
	STIMULUS X GROUP	n.s.
	INHIB X REC X GROUP	n.s.
	INHIB X STIM X GROUP	n.s.
	REC X STIM X GROUP	n.s.
	INHIB X REC X STIM X GROUP	N/A (?)
INVENTIONS	GROUP	DAT<EC; DAT<AC

		RESULTS
	INHIBITION X GROUP	n.s.
	RECALL X GROUP	n.s.
	STIMULUS X GROUP	n.s.
	INHIB X REC X GROUP	In DAT LI<HI with R2; In EC LI<HI with R3
	INHIB X STIM X GROUP	n.s.
	REC X STIM X GROUP	n.s.
	INHIB X REC X STIM X GROUP	n.s.
OMISSIONS	GROUP	DAT<EC; DAT<AC
	INHIBITION X GROUP	n.s.
	RECALL X GROUP	With R1: DAT=EC; DAT=AC With R2: DAT=EC; DAT<AC With R3; R4: DAT<EC; DAT<AC
	STIMULUS X GROUP	n.s.
	INHIB X REC X GROUP	n.s.
	INHIB X STIM X GROUP	n.s.
	REC X STIM X GROUP	W>N in DAT with R4
	INHIB X REC X STIM X GROUP	n.s.

Key: DAT=Participants with DAT; EC=Elderly controls; AC=Adult controls
LI=Low Inhibition; HI=High Inhibition
R1;R2;R3;R4=1 item to recall; 2 items to recall etc.; W=Words (i.e. nouns); N=Numbers
> = better performance (i.e. more items recalled or fewer errors);
< = worse performance (i.e. fewer items recalled or more errors)
n.s. = not significant;

4.3.2. Numerical Tasks

In these tasks only the DAT group and the group of healthy elderly (EC) were compared. Due to the violation of normality assumption for the variables tested, a non-parametric analysis was performed.

4.3.2.1. Writing Numerals

The two groups showed no significant difference in writing Arabic numerals to dictation[140] nor in writing words to dictation[141].

As illustrated in Figure 4.32, the DAT group performs worse than the EC group in writing number words to dictation [Mann-Whitney U-Test = 77.50; $p < 0.05$]. The majority of errors were due to the intrusion of the Arabic code (e.g.

[140] [Mann-Whitney U-Test = 141.00; p>0.05]
[141] [Mann-Whitney U-Test = 119.50; p>0.05]

trecento15 when they heard "trecentoquindici" that is three-hundred and fifteen in Italian).

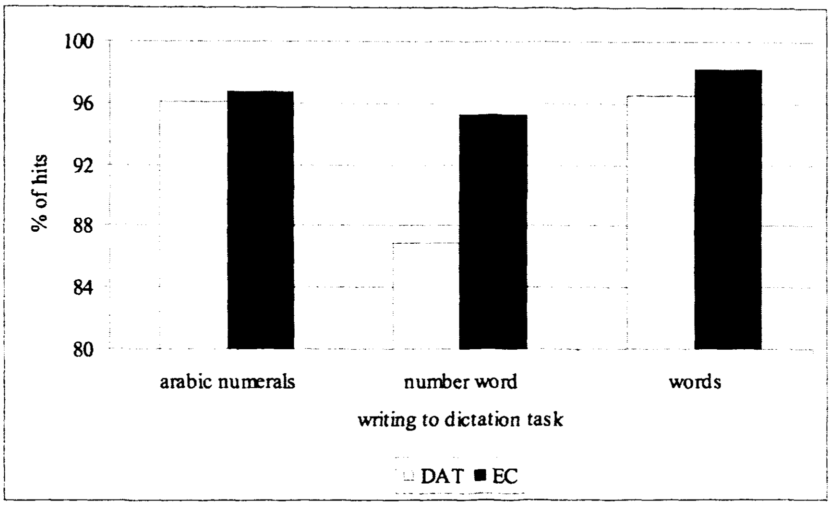

Figure 4. 32: Numerical tasks - Writing numerals - comparison between DAT and EC

4.3.2.2. Reading Numerals and Transcoding Tasks

The two groups show no significant difference in reading Arabic numerals[142], nor number-words[143]. Moreover, there is no significant difference in transcoding from Arabic to verbal code[144], or in transcoding from verbal to Arabic code[145].

4.3.3. Calculation Tasks

Only the DAT group and the EC group were compared in the calculation tasks. Due to the violation of normality assumption for the variables tested, for the arithmetical facts a non-parametric analysis was performed. For the Jackson & Warrington (1986) test and the Complex Mental Calculation task, an ANOVA was used. Bonferroni correction was used when multiple comparisons were

[142] [Mann-Whitney U-Test = 138.00; p>0.05]
[143] [Mann-Whitney U-Test = 120.50; p>0.05]
[144] [Mann-Whitney U-Test = 114.50; p>0.05]
[145] [Mann-Whitney U-Test = 105.00; p>0.05]

performed on the data, and all the significance values reported include this correction where necessary.

4.3.3.1. *Arithmetical Facts*

As far as the percentage of correct responses (hits) was concerned, the two groups showed no significant difference in the performance on addition[146], subtraction[147], or multiplication[148].

When comparing the performance (measured as percentage of hits) in the different arithmetical operations within each group with the Friedman test, the results showed that there is a significant difference between operations in both DAT [$\chi^2(2) = 13.53$, $p<0.002$] and EC [$\chi^2(2) = 14.28$, $p<0.002$]. These differences were further analysed with the Wilcoxon Signed Ranks Test. Figure 4.33 shows that the significant difference is due to performance on multiplication being lower than performance on addition (both in DAT [$Z = -3.06$, $p<0.005$] and in EC[$Z = -2.36$, $p<0.02$]) and on subtraction (both in DAT [$Z = -3.15$, $p<0.005$] and in EC [$Z = -2.40$, $p<0.02$]).

[146] [Mann-Whitney U-Test = 139.00; p>0.05]
[147] [Mann-Whitney U-Test = 118.50; p>0.05]
[148] [Mann-Whitney U-Test = 106.50; p>0.05]

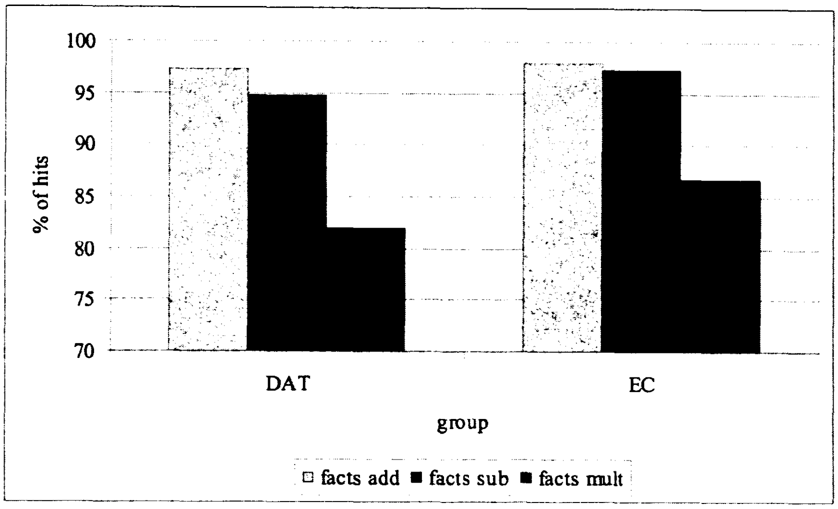

Figure 4. 33: Calculation tasks - Arithmetical facts - comparison between levels of OPERATION in DAT and EC

4.3.3.2. Jackson & Warrington Test

A 2x2x3 mixed design ANOVA was conducted to see the differences in the performance on mental calculation between the two groups in the Jackson & Warrington (1986) test, and to see effects due to the type of operation and to difficulty of the task (measured as the number of carryings/borrowings required for the solution of the problem). The between-subjects factor was GROUP with two levels (DAT and EC), and the within-subjects factors were: OPERATION with two levels (ADD and SUB), and CAR/BOR with three levels (0 c/b; 1 c/b; 2 c/b). The dependent variable was the percentage of correct responses (hits) in the Jackson & Warrington test.

No main effect of GROUP was found[149], indicating that the performance of the two groups does not significantly differ.

The main effect of OPERATION is significant [F(1,31) = 39.64; p<0.001], due to the performance on addition being better than the performance on subtraction.

[149] [F(1,31) = 2.42; p>0.05]

The main effect of CAR/BOR is also significant [F(1,43)= 27.05; p<0.001]. A polynomial contrast confirms that this factor shows a significantly linear decrease [F(1,31) = 43.00; p<0.001]. This can be observed in Figure 4.34, where the percentage of hits decreases proportionately to the increase in the number of carryings/borrowings involved in the solution of the problem. No other significant trend was observed.

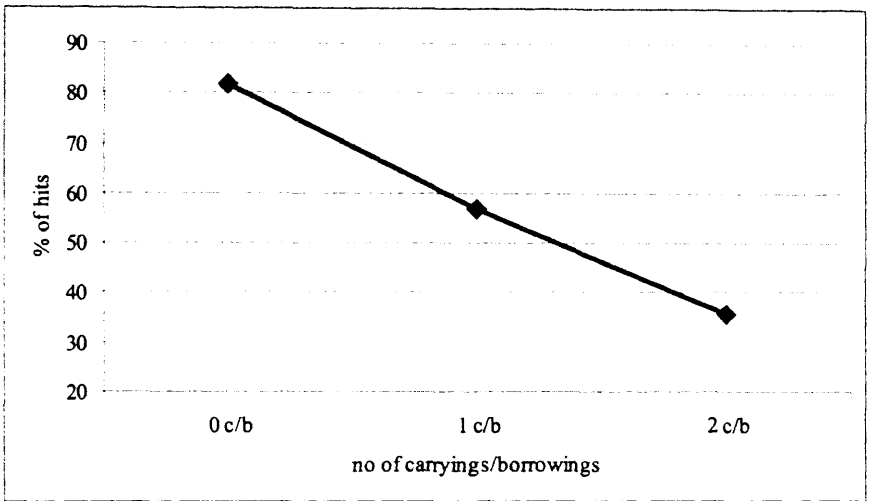

Figure 4. 34: Calculation tasks - Jackson & Warrington test - main effect of CAR/BOR

No significant interaction was found[150].

4.3.3.3. Complex Mental Calculation

A 2x2x3 mixed design ANOVA was run to see the differences in the performance on complex mental calculation with visual presentation between the two groups, and to see effects due to the type of operation or to the difficulty (measured as the number of carryings/borrowings required for the solution of the problem). The independent variables were the same as in the analysis of the

[150] (OPERATION X GROUP [F(1,31) = 0.08; p>0.05]; CAR/BOR X GROUP [F(1,43) = 1.00; p>0.05]; OPERATION X CAR/BOR [F(2,62) = 1.79; p>0.05]; and OPERATION X CAR/BOR X GROUP [F(2,62) = 1.60; p>0.05]).

Jackson Test, and the dependent variable was the percentage of correct responses (hits) in the complex mental calculation task.

No main effect of GROUP was found [F(1,30) = 3.03; p>0.05

The effects of OPERATION is significant [F(1,30) = 50.31; p<0.001], due to the performance on addition being better than the performance on subtraction.

The main effect of CAR/BOR is significant [F(1,43)= 33.21; p<0.001]. A polynomial contrast confirms that this factor shows a significantly linear decrease [F(1,30) = 55.71; p<0.001], as illustrated in Figure 4.35. No other significant trends were observed.

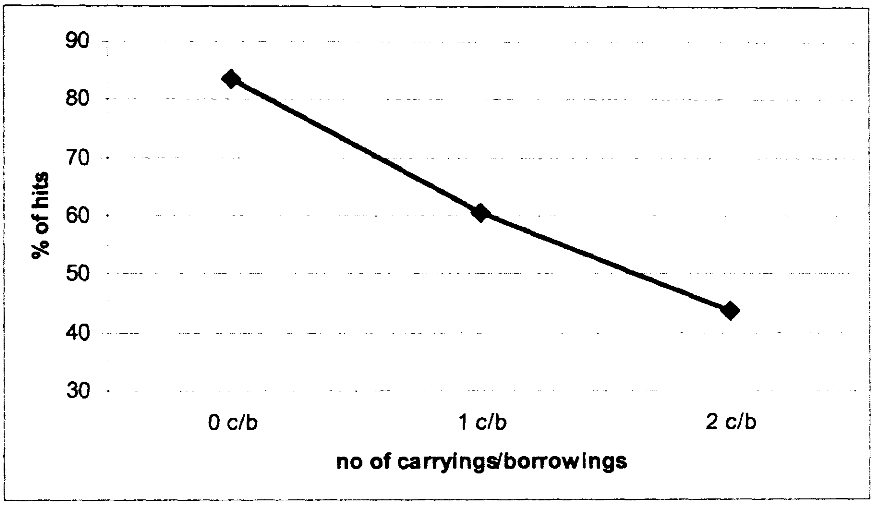

Figure 4. 35: Calculation tasks - Complex mental calculation - main effect of CAR/BOR

The interaction OPERATION X CAR/BOR is significant [F(2,60) = 16.12; p<0.001]. In order to investigate this interaction, a Paired Samples t-test was conducted, comparing the performance on addition and subtraction at each level of CAR/BOR. As illustrated in Figure 4.36, the difference between the two levels of addition and subtraction is only significant with 1 c/b [t(31)= 4.27, p<0.005] and 2 c/b [t(31)= 6.24, p<.005], but not with 0 c/b[151].

[151] [t(31)= 0.98, p>0.05]

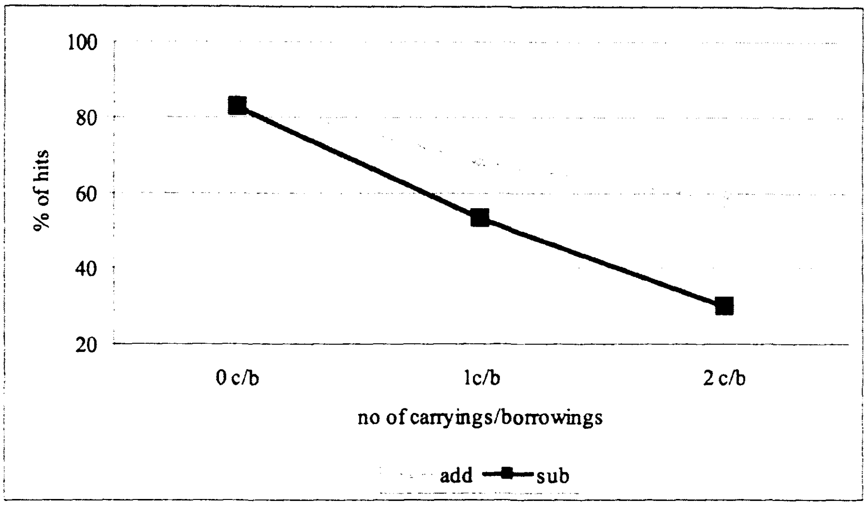

Figure 4. 36: Calculation tasks - Complex mental calculation - interaction OPERATION X CAR/BOR

Operation and number of carryings/borrowings involved also interact with group: the interaction OPERATION X CAR/BOR X GROUP is significant [F(2,60) = 5.47; p<0.01][152]. A Paired Samples t-test was conducted comparing the performance on addition and subtraction at each level of CAR/BOR, in each one of the groups. Figure 4.37 shows that in DAT the difference between addition and subtraction is significant at all levels of CAR/BOR (with 0 c/b [t(17)= 2.86, p<0.05];with 1 c/b [t(17)= 3.22, p<0.01] and 2 c/b [t(17)= 3.54, p<.01]; whereas in EC this difference is only significant with 1 c/b [t(13)= 2.76, p<.05] and 2 c/b [t(13)= 5.90, p<0.005], but not with 0 c/b[153].

[152] The other interactions (OPERATION X GROUP [F(1,30) = 0.06; p>0.05] and CAR/BOR X GROUP [F(1,43) = 2.43; p>0.05]) were not significant.
[153] [t(13)= -2.09, p>0.05]

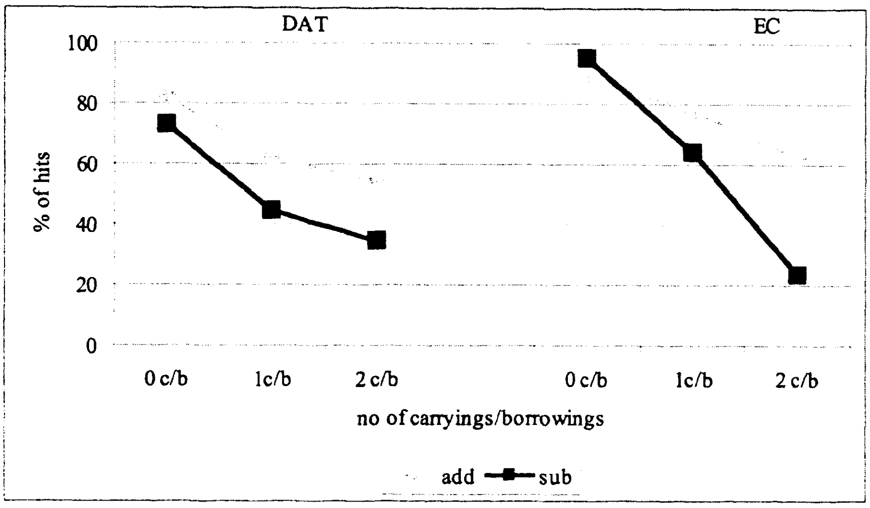

Figure 4. 37: Calculation tasks - Complex mental calculation - interaction OPERATION X CAR/BOR X GROUP

4.3.3.4. Complex Mental Calculation: Verbal versus Visual Presentation

A 2x2x2 mixed design ANOVA was run to investigate the differences in performance between the two groups comparing verbal and written presentation and also addition and subtraction. The between-subjects factor was the same as in the previous analysis, and the within-subjects factors were: OPERATION with two levels (ADD and SUB), and PRESENTATION with two levels (VERBAL and VISUAL). The dependent variable was the percentage of correct responses (hits) in the common items between the Jackson & Warrington (1986) test and Complex Mental Calculation Task (i.e. all the items of the Jackson & Warrington test and the same 28 items in the Complex Mental Calculation Task).

No main effect of GROUP[154], or OPERATION[155] was found.

The main effect of PRESENTATION is significant [$F(1,30)= 9.99$; $p<0.005$], and it is explained by an increase in performance when the presentation

[154] [$F(1,30) = 4.05$; $p>0.05$]
[155] [$F(1,30) = 0.44$; $p>0.05$]

is visual (i.e. the problem is written in front of the participants while they try to solve it), compared to when the examiner reads the stimuli aloud (i.e. the participant has to remember the problem in order to solve it).

The interaction OPERATION X PRESENTATION is significant [$F(1,30) = 5.26$; $p<0.05$][156]. A Paired Samples t-test was conducted, comparing the performance with visual and verbal presentation at each level of OPERATION. Figure 4.38 shows that the difference between verbal and visual presentation is only significant with the additions [$t(31)= -4.17$, $p<0.005$], but not with the subtractions[157].

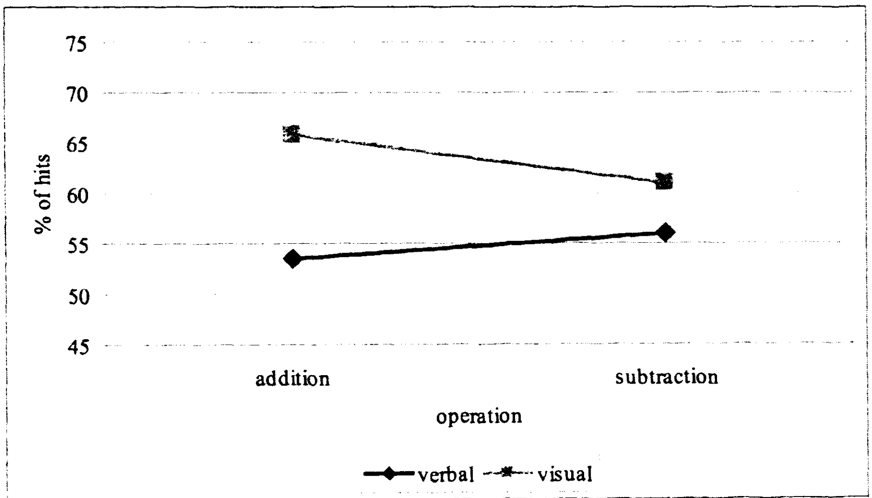

Figure 4. 38: Calculation tasks - Complex mental calculation -verbal vs. visual - interaction OPERATION X PRESENTATION

4.3.4. The Relationship between Working Memory and Calculation

In order to understand the relationship between WM and complex mental calculation, linear regression analyses were conducted for the two groups of

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156 The other interactions (OPERATION X GROUP [$F(1,30) = 1.72$; $p>0.05$]; PRESENTATION X GROUP [$F(1,43) = 0.003$; $p>0.05$]); and OPERATION X PRESENTATION X GROUP [$F(1,30) = 0.006$; $p>0.05$] were not significant.

157 [$t(31)= -1.53$, $p>0.05$].

participants to investigate possible associations between measures of WM and performance on complex mental calculation tasks.

A linear regression analysis was performed with the performance on the Jackson & Warrington (1986) test as a dependent variable and digit span test forward as the independent variable, and another regression analysis with Complex Mental Calculation task as a dependent variable and digit span test forward as the independent variable. This analysis shows that digit span forward does not significantly explain the variance in the Jackson & Warrington (1986) test neither in the DAT group[158], nor in the EC group[159]. It also does not explain for the variance in the Complex Mental Calculation task either in the DAT group[160], or in the EC group[161].

A linear regression analysis was then performed with the performance on the Jackson & Warrington (1986) test as a dependent variable and digit span test backwards as the independent variable, and another regression analysis with Complex Mental Calculation task as a dependent variable and digit span test backwards as the independent variable. The results show that the performance on the digit span backwards explains 33.4% of the variance in the Jackson & Warrington (1986) test in the DAT group [$R^2 = 0.334$; $p < 0.02$], and 40.7% of the variance in the EC group [$R^2 = 0.407$; $p < 0.02$]. It also explains 32.20% of the variance in the Complex Mental Calculation task in the DAT group [$R^2 = 0.322$; $p < 0.02$], and 54.1% of the variance in the EC group [$R^2 = 0.541$; $p < 0.005$].

Other two regression analyses studied WM total recall as an independent variable and performance on the Jackson & Warrington (1986) test and in the

158 [$R^2 = 0.138$; $p>0.05$]
159 [$R^2 = 0.192$; $p>0.05$]
160 [$R^2 = 0.178$; $p>0.05$]
161 [$R^2 = 0.271$; $p>0.05$]

Complex Mental Calculation task respectively as dependent variables. This shows that WM total recall does not significantly explain the variance in the Jackson & Warrington (1986) test neither in the DAT group[162], nor in the EC group[163]. It also does not explain the variance in the Complex Mental Calculation Task in the EC group[164], but it does explain 34.7% of the variance in this task, in the DAT group [R^2 =0.347; p<0.02], as illustrated in Figure 4.39.

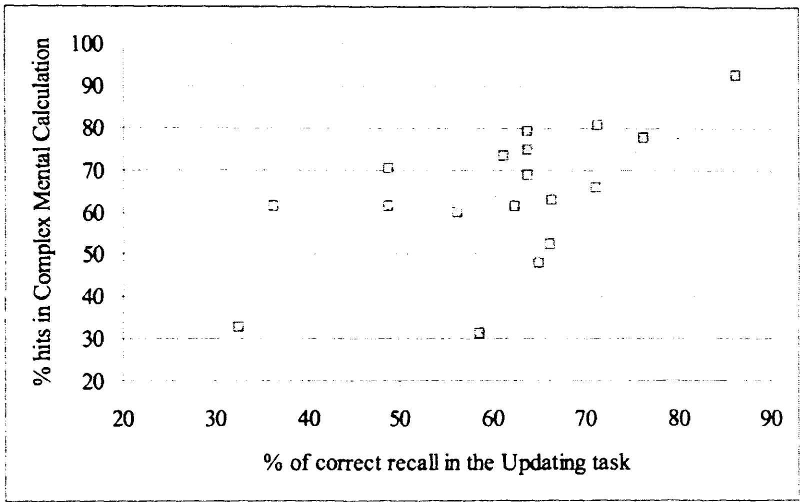

Figure 4. 39: Scatterplot of recall performance on the Updating task and performance on Complex Mental Calculation task (DAT group)

Other regression analysis studied WM total intrusions from the same list as an independent variable and performance on the Jackson & Warrington (1986) test and in the Complex Mental Calculation task respectively as dependent variables. This shows that WM total intrusions from the same list does explain 38.1% of the variance in the Jackson & Warrington (1986) test in the DAT group [R^2 = 0.381; p <0.01], as it can be observed in Figure 4.40, but does not significantly explain the variance in this test in the EC group[165].

162 [R^2 =0.213; p>0.05]
163 [R^2 =0.211; p>0.05]
164 [R^2 =0.228; p>0.05]
165 [R^2 = 0.131; p>0.05]

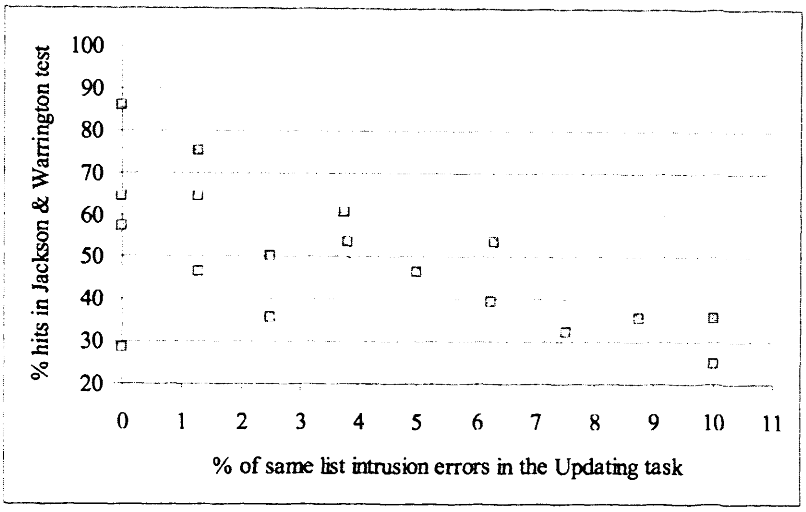

Figure 4. 40: Scatterplot of same list intrusion errors in the Updating task and performance on Jackson & Warrington test (DAT group)

It also does not explain the variance in the Complex Mental Calculation Task in the EC group[166], but it does explain 27.7% of the variance in this calculation task, in the DAT group [R^2 =0.277; $p<0.05$] (see Figure 4.41).

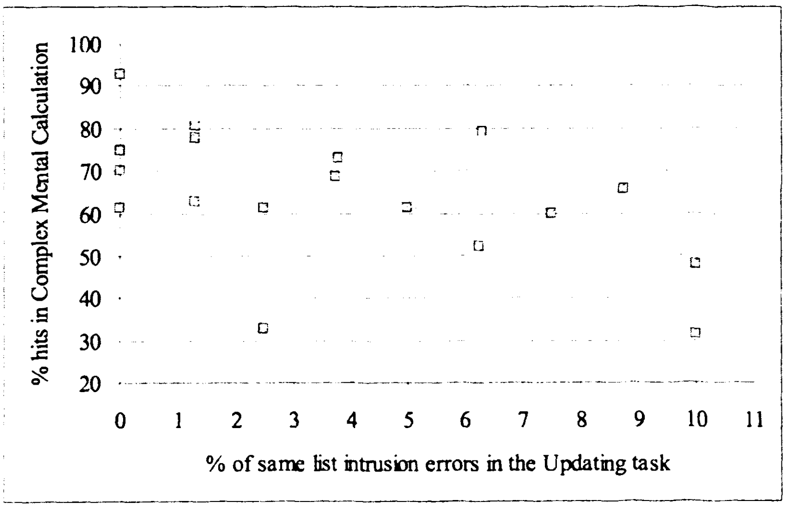

Figure 4. 41: Scatterplot of same list intrusion errors in the Updating task and performance on Complex Mental Calculation task (DAT group)

166 [R^2 =0.033; $p>0.05$]

4.4. Discussion

4.4.1. The effects of DAT on WM

The first aim of this study was to investigate the processes studied in the previous chapter in people with DAT, investigating whether DAT selectively affects specific components of WM.

As far as the span tests were concerned: similar overall effects of stimulus and length were found as in previous studies, with performance on the digit span being better than performance on the span tests involving other bi-syllabic words (i.e. nouns and proper names) and performance on recalling 2-digit numbers being worse than performance on the span tests involving other words 3 to 5-syllables-long (i.e. nouns and proper names); no length effect was found for nouns and proper names.

Differences were also expected in the digit span backwards where a lower performance was predicted in the DAT group compared to their controls. The predictions and results on the group effects of the span test are summarised in Table 4.4. In accordance with the idea that, at least at the initial stages of the disease, PL is not affected in DAT (Carlesimo et al., 1994; Collette et al., 1998), no other differences between groups were expected in the span tests. The results were in contrast to the prediction in that people with DAT performed more poorly than their adult controls (matched for education) in all of the span tests. Compared to their elderly controls, instead, people with DAT showed a worse performance only in the span tests requiring recalling long (3-5 syllables) nouns and proper names, but no difference in the digit span backwards. Moreover, comparing the performance of the elderly to the performance of adults it emerged that the older group' s performance is worse in recalling bi-syllabic nouns (but not proper names). This is consistent with the findings of the previous chapter, where a decrease of performance with ageing was found in the span tasks forward when recalling shorter items. This was interpreted as a decrease in the functioning of the PL (because it suggests a reduced length effect). Also the absence of a difference in performance between adults and elderly in the backwards span is consistent with the results of the previous chapter, where no difference was found between the group of adults and the group of elderly. More difficult to explain is the absence of the expected difference in performance on the backwards span between healthy elderly and elderly with DAT. This could be due to the fact that the DAT participants were at the early stages of the disease. Their performance on a task like the digit span backwards, where the demands on maintenance are coupled with demand on control processes, was in fact poorer than the performance of both the group of adults and the group of elderly, but in the latter case this was not strong enough to reach statistical significance. It could therefore be that with the progression of the disease this difference would become significant. This is speculative and it would be necessary to investigate this with a longitudinal study to enable firm conclusions.

Taken together these results seem to suggest that both PL and CE are affected in DAT, where the decline in PL functioning is partly due to the aging process (increased difficulties in recalling shorter items) and partly to the dementing process (the additional difficulty in recalling longer items). This is in accordance with the suggestion of Collette et al. (1998) that DAT can affect several components of WM (phonological store, articulatory rehearsal system and CE mechanism) but that not necessarily all aspects of CE are affected.

Table 4. 4: Span tests - predictions and results

SPAN TASKS		PREDICTIONS	RESULTS
No	2 syllables	DAT=EC;DAT=AC	DAT=EC; DAT<AC
	3/5 syllables	DAT=EC;DAT=AC	DAT=EC; DAT<AC
N	2 syllables	DAT=EC;DAT=AC	DAT=EC; DAT<AC
	3/5 syllables	DAT=EC;DAT=AC	DAT<EC; DAT<AC
PN	2 syllables	DAT=EC;DAT=AC	DAT=EC; DAT<AC
	3/5 syllables	DAT=EC;DAT=AC	DAT<EC; DAT<AC
SPAN BACKWARDS		DAT<EC; DAT<AC	DAT=EC; DAT<AC

Key: DAT=Participants with DAT; EC=Elderly controls; AC=Adult controls
No=Number; N=Noun; PN=Proper names
> = better performance; < = worse performance

The possibility that DAT selectively affects specific components of WM was also investigated. In particular, it was expected that in people with DAT, poorer performance on both recall (maintenance) and inhibition of irrelevant information (control) compared to the adult controls would be evident, and poorer performance on control processes compared to the elderly controls. This would be consistent with Collette et al.'s (1998) idea, and supported by other studies (Belleville et al., 1996; Collette et al., 1999), which suggests that several components of WM can be affected by DAT. The main difference between the current study and these studies, however, is the idea of maintenance processes of WM, as the process allowing the temporary storage of information, which could then be manipulated by CE control processes. Therefore, this notion of maintenance processes, despite being related to the correct functioning of the PL, is quite similar to what Vecchi and Cornoldi (Vecchi & Cornoldi, 1999; Cornoldi & Vecchi, 2000) referred to as active processing of information, as opposed to passive processing. The authors regarded passive storage as the retention of (visuo-spatial) information that is encoded and not modified. They suggested that encoding could happen as a reaction to an external stimulus, to information from

LTM or from mental manipulation by another part of the cognitive system. Active storage is regarded as the manipulation, integration or transformation of stored (visuo-spatial) information. The authors also suggested that the outcome of active processing may be held in the passive store or determine a response. They argue that passive and active storage stand along a continuum, with the position on the continuum determined by the amount of active processing required (Cornoldi & Vecchi, 2000). They suggest that (visuo-spatial) tasks that require storage and some basic active processing (e.g. rehearsal), are closer to the passive end of the spectrum than tasks that involve manipulation of the to-be-processed information.

In the current study, the span tests involving the activity of the PL would be close to the passive storage end of the continuum, whereas the recall of information in the updating task would be considered closer to the active processing end. In particular, the maintenance of relevant information would be closer to the active end than performance on the span tests, but closer to the passive end than the ability to inhibit irrelevant information (control processes). In this study, both maintenance and control processes were expected to be affected by DAT, in accordance with Baddeley's suggestion (1986). However, only maintenance was actually found to be affected. Other predictions, supported by the data, were that recall performance in people with DAT would be more affected by load on maintenance processes than in their controls, and that performance in people with DAT on both recall and inhibition of irrelevant information would be more affected by load on control processes than in their controls. This would be consistent with the idea that in patients with DAT progressively more control resources are required, even for tasks that are almost automatic for normal elderly (Spinnler, 1991), and with the idea that people with DAT are sensitive to tasks in which CE involvement is particularly high (Jorm, 1986).

Table 4. 5: Updating task - Effects of group - predictions and results

		PREDICTIONS	RESULTS
RECALL	GROUP	DAT<EC;DAT<AC	DAT<EC; DAT<AC
	INHIBITION X GROUP	LI>HI in DAT	LI>HI in DAT; EC; AC (?)
	RECALL X GROUP	DAT<EC and DAT<AC with R2; R3; R4	DAT<EC and DAT<AC with R2; R3; R4
	STIMULUS X GROUP	n.s.	n.s.
	INHIB X REC X GROUP	In DAT LI>HI with lower load on maintenance than in EC and AC	In DAT LI>HI with R2; R3; R4 In EC LI>HI with R3;R4 In AC LI>HI with R4
	INHIB X STIM X GROUP	n.s.	n.s.
	REC X STIM X GROUP	In DAT W>N with lower load on maintenance than in EC and AC	In DAT W=N with R1; R2; R3; R4 In EC and AC W>N with R4
	INHIB X REC X STIM X GROUP	-	n.s.
SAME LIST INTRUSIONS	GROUP	DAT<EC;DAT<AC	n.s.
	INHIBITION X GROUP	LI>HI in DAT	LI>HI only in DAT
	RECALL X GROUP	n.s.	n.s.
	STIMULUS X GROUP	n.s.	n.s.
	INHIB X REC X GROUP	n.s.	n.s.
	INHIB X STIM X GROUP	n.s.	n.s.
	REC X STIM X GROUP	n.s.	n.s.
	INHIB X REC X STIM X GROUP	-	n.s.

Key: DAT=Participants with DAT; EC=Elderly controls; AC=Adult controls; LI=Low Inhibition; HI=High Inhibition; R1;R2;R3;R4=1 item to recall; 2 items to recall etc.; W=Words (i.e. nouns); N=Numbers; > = better performance (i.e. more items recalled or fewer errors); < = worse performance (i.e. fewer items recalled or more errors); n.s. = not significant; - = no prediction made

Table 4.5 summarises the predictions and results of the group effects on the updating task. The prediction that maintenance processes would be affected by DAT was confirmed: the group of participants with DAT perform poorly compared to the other two groups in the updating task. Adults and elderly participants do not differ from each other. This result is in contrast to the findings reported in the previous chapter, where a decrease in recall performance (maintenance) is present with ageing. This is interpreted as supporting the idea that that ageing provokes a decrease in the "total processing capacity" of the CE (Baddeley, 1986). The contrasting result evident in the present data, however, seems to support Van der Linden et al.'s (1994) argument that the reduction of CE resources with aging does not involve CE storage. This discrepancy between the data presented in the studies discussed in this and the previous chapter, limits the degree to which conclusions can be drawn from these studies, about the effects of ageing on maintenance processes. The expected impairment in control processes was not as predicted. No difference was found between groups in the production of same list intrusion errors. The DAT group differed from the other two groups in the production of invention errors and omission errors. This suggests than in DAT, memory processes are generally impaired and the failure to recall correct information is evident in the omission of a response or in a "false recall" (i.e. recall of never presented items). This could be considered a form of provoked confabulation, which, as suggested by Kopelman (1987; 2002), may reflect a normal response to a faulty memory. Alternatively, it could reflect a deficit of some aspect of executive function. Shapiro et al. (1981) suggest that several deficits may contribute to confabulation: a self-monitoring deficit; a failure to inhibit memory errors; or frequent perseverations. Assuming a CE deficit in DAT, the possibility that the increase of invention errors is due to a failure to inhibit memory errors seems the most likely. This idea is supported by the effect of load on control processes in the production of invention errors, with fewer inventions being produced when fewer demands are placed on control processes. The possibility that invention errors are secondary to a memory deficit and not the reflection of an executive dysfunction cannot be discarded (Kopelman, 2002). It is of note, however, that this pattern was not found in healthy participants.

The results are also consistent with the idea that in patients with DAT progressively more control resources are required, even for tasks that are almost automatic for healthy elderly adults (Spinnler, 1991). It was also expected that recall performance in people with DAT would be more affected by load on maintenance processes than in their controls. This was confirmed by the results indicating that performance in the DAT group was worse than performance in the other two groups at all levels of load on recall, except in the condition where the demands on maintenance were kept to a minimum. The prediction that performance in people with DAT with both recall and the inhibition of irrelevant information would be more affected by load on control processes than in the control groups is supported by the finding that only in the DAT group more same list intrusion errors were produced with a high load on control processes. Moreover, in the DAT group the effect of load on control processes on recall performance was present at lower levels of load on maintenance than in the other two groups. This pattern of results supports the idea that people with DAT are sensitive to tasks in which CE involvement is particularly high (Jorm, 1986).

4.4.2. Overall WM effects

The same main effects found in the group of adults and elderly participants studied in the previous chapter were expected for this study. The predictions were confirmed by the results. The only differences found were in the production of previous list intrusions and inventions. In particular, the effect of stimulus on the production of previous list intrusion errors is present in the current data in the condition of lower load on maintenance. Furthermore, an effect of load on control processes is evident in the production of invention errors, with fewer inventions produced when fewer demands are placed on control processes. A further interesting difference is present in the quality of omission errors: unlike the groups studied so far, DAT participants produced more omission errors when recalling words than when recalling numbers.

4.4.3. Performance on Numerical and Calculation tasks

Another aim of this study was to investigate the performance of participants with DAT on numerical and calculation tasks. The first prediction was that participants with DAT would perform more poorly in the transcoding tasks than healthy elderly. The results did not confirm this prediction. The only difference evident between DAT group and their aged-matched controls is when writing number-words to dictation. This is mostly due to the intrusion of the Arabic code as part of the number-word. This result could stem from the failure to inhibit a more prepotent response (i.e. to use Arabic numerals) (Tegner & Nyback, 1990). Interestingly this failure manifests itself only when writing to dictation and not in the other transcoding tasks, and it may therefore have something to do with phonological maintenance. As predicted, there is no difference between groups in performance on the arithmetical facts, supporting the idea that declarative knowledge is intact in people with DAT (Girelli et al., 1999). Contrary to expectations, no difference was found between groups in complex mental calculation. This kind of task is supposed to require an efficient executive control, and the failure to find a deficit in this task would suggest that executive processes are relatively spared in this group. The failure to find such a difference between participants with DAT and healthy controls could be also related to the mildness of the disease in the group studied here. Further interesting results are that with arithmetical facts, performance on multiplication is worse than performance on addition and subtraction. It is of note that the majority of mistakes made by both the participants in the DAT and EC has occurred when the multiplication facts retrieval involved zero multiplicands. This is consistent with the findings of a previous study showing that for problems involving zero multiplicands healthy older adults and people with probable Alzheimer's disease show significantly higher error rates than younger adults (Allen, Bucur, Lemaire, Duverne, Ogrocki, & Sanders, 2005). The authors of the study suggest that rule retrieval of correct solutions in memory for problems involving zero operands is impaired in both of these older groups. Unfortunately this was not possible to demonstrate in the present study, as an adult control group was not included. A further interesting finding was that in both complex mental calculation tasks performance with addition was better than performance with subtraction.

The finding that performance with verbal presentation of multi-digit problems is worse than with visual presentation was expected and can be explained with the greater demands on the phonological loop in the auditory condition (Logie, Gilhooly, & Wynn, 1994). It could also be due to the suggested reduced processing capacity of the Central Executive with ageing suggested by findings of the study presented in the previous chapter.

A further prediction was that an advantage for problems involving fewer carries or borrowings, and therefore fewer steps, would be evident. This advantage is confirmed in the current study, and can be interpreted as a consequence of the increase of load on the central executive of WM. It has in fact been suggested that problems involving carries (or borrowings) may be more demanding because, if it is true that CE has limited capacity, they require the coordination of several steps by the Central Executive. However, it is not clear at present whether they are more demanding because of the differential demands of retrieval for easier versus harder arithmetic facts (DeStefano & LeFevre, 2004). Furst and Hitch's (2000) findings support the view that an increased number of carryings (or borrowings) increases the general resource demand required to solve the problem. The finding that in participants with DAT there is an advantage for performing addition problems (compared to subtraction problems) with no carrying or borrowings, and therefore, possibly the lowest level of load on WM, could indicate that despite this group being only very mildly impaired in their calculation processes, their resources are more limited than healthy controls, requiring greater central executive demand at lower levels of load.

4.4.4. Working memory and calculation

A final question addressed by this study is whether there is a relationship between numerical and calculation performance and the functioning of WM in DAT patients, and if this relationship is attributable to certain components of WM more than to others. In order to address this, regression analyses were conducted for both groups in order to see how much of the variance in the calculation tasks (hypothesised but not found to be impaired in DAT) was explained by their performance on the WM tasks (that were also expected to be impaired in the DAT group). The results of these analyses show that the relationship between calculation tasks and updating tasks (both maintenance and control) is only found in the DAT group. These results suggest that although calculation performance is not affected by the dementing process, at least at this early stage, people with DAT use more maintenance and control resources from WM in order to perform tasks that are more automatic for healthy elderly. It is also of note that when investigating the performance of both groups in the digit span backwards task, the processes involved explain a large proportion of the variance in the calculation tasks. This suggests that the maintenance and control processes required to perform the digit span task (backwards) are similar to those involved in complex mental calculation in both normal and abnormal aging. In future work, it would be interesting to investigate this relationship in a group of healthy adults, in order to understand the influence of these processes on complex mental calculation across the life span.

In summary, the data from the present study add to our knowledge of the effects of DAT on WM processes, and particularly of maintenance and control processes. The data confirmed a decline in both PL of CE as a consequence of DAT. In particular, people with DAT present with affected maintenance processes, and they require more control resources even for tasks almost automatic for their peers. Moreover the data presented in this chapter also adds to the understanding of the effects of WM on mental calculation, and more specifically with respect to the decline in WM observed as a consequence of DAT. In fact the results allow suggesting that, although calculation performance is not significantly affected by DAT (at least at an early stage), people with this condition require more maintenance and control resources from WM to perform calculation tasks, compared to healthy controls. It would be interesting to understand whether similar effects would be found in other conditions known to affect WM. The next chapter will investigate the effects of frontal lobe lesions on maintenance and control processes of WM, and how these affect mental calculation in this group.

CHAPTER 5: WORKING MEMORY AND CALCULATION: A PRELIMINARY STUDY OF FRONTAL AND TEMPORO-OCCIPITAL PATIENTS

5.1. Introduction

Since the end of the 19th century patients with lesions to the frontal lobes have been investigated to understand the involvement of the frontal lobes in complex cognitive functions (Jackson, 1884; Brickner, 1936; Ackerley, 1964; Luria, 1966).

Luria (1966; 1969) suggested that one of the main functions of the human frontal lobes is the selection and regulation of cognitive planning, and this position has been supported by many others (Shallice & Evans, 1978; Fuster, 1980; Shallice, 1982). Shallice (1982) suggested that the Supervisory Attentional System (SAS) of Norman and Shallice's (1986) model is a system specialised to program, regulate and verify activities and actions. The SAS has also been suggested by Baddeley (1986) as a good way to conceptualise the CE of WM. All this suggests that the study of patients with frontal lobe lesions is an interesting means of investigating WM and complex cognitive functions that require planning, regulation and control (e.g. calculation).

5.1.1. Working Memory and frontal lobes

In recent years accumulating evidence suggesting that the frontal cortex plays a critical role in WM has been gathered, coming from studies on patients (Petrides & Milner, 1982; Owen, J.D., Sahakian, Polkey, & Robbins, 1990; Owen, Sahakian, Semple, Polkey, & Robbins, 1995; Owen, Morris, Sahakian, Polkey, & Robbins, 1996) and non-human primates (Goldman-Rakic, 1987; Petrides, 1994a) and from functional neuroimaging studies (Jonides, Smith, Koeppe, Awh, Minoshima, & Mintun, 1993; Petrides, Alivisatos, Evans, & Meyer, 1993a; 1993b; McCarthy, Blamire, Puce, Nobre, Bloch, & Hyder, 1994; Smith, 1995; Smith, Jonides, & Koeppe, 1996; Courtney, Ungerleider, Keil, & Haxby, 1996; Gold, Berman, Randolph, Goldberg, & Weinberger, 1996; Goldberg, Berman, Randolph, Gold, & Weinberger, 1996; Owen, Evans, & Petrides, 1996; Owen, Doyon, Petrides, & Evans, 1996; Sweeney, Minutun, Kwee, Wiseman, Brown, Rosenberg, & Carl, 1996).

These studies identified the lateral frontal cortex as the area involved in WM. A distinction has been made between parts of this area responsible for different aspects of WM. The two main positions both make a distinction between dorsolateral frontal region and ventrolateral frontal region but they ascribe different functions to these areas.

According to the "domain specific" or "modality specific" model (Goldman-Rakic, 1987; 1994; 1995; Levy & Goldman-Rakic, 2000), WM processes are organised within the lateral frontal cortex according to the modality of the information to be processed. Goldman-Rakic (1994; 1995) suggests that the dorsolateral prefrontal cortex (DPFC) is concerned with memory for spatial material whereas the ventrolateral areas are concerned with memory for non-spatial material.

Petrides (1994a; 1995) suggests an alternative view according to which WM processes are organized on the basis of the processing required and not to the modality of the material to remember ("process-specific" model). More specifically, dorsolateral frontal regions are involved when active manipulation and monitoring of information to hold in memory is required; whereas ventrolateral frontal lobe regions are involved in organising sequences of responses based on explicit retrieval of information from posterior association areas.

In a meta-analysis study, Owen (1997) argued that there is more support for the latter hypothesis as there is greater evidence suggesting that specific regions within the dorsolateral and ventrolateral frontal cortex make equal functional contributions to both spatial and non-spatial WM.

According to Smith and Jonides (1997) there are separate WM systems for spatial (localized in the right hemisphere) and verbal information (localized in the left hemisphere). The authors made a distinction between phonological storage, mediated by the posterior-parietal area of the brain, and phonological rehearsal, mediated by the anterior areas of the brain involved in speech (e.g. Broca's area, premotor cortex and supplementary motor cortex). This distinction is also supported by an experiment by Paulesu, Frith and Frackowiak (1993) who compared a memory task (item-recognition) with a rhyming task (involving similar processes as rehearsal) and found that in the former, the left posterior parietal cortex became activated and the Broca's area was no longer activated, as it was with the latter.

Smith and Jonides (1997) also claimed that for both spatial and verbal WM systems the passive storage of information involves the posterior areas of the brain and the active maintenance of information involves the frontal areas of the brain. They also suggest that there may be separate components devoted to processing the contents of WM, and they suggest that these are localized in the prefrontal cortex.

The authors studied changes in brain activation (using positron emission tomography -PET-) during a verbal WM task when manipulating memory load. They found that all the areas hypothesised to relate to the relevant components of WM show increased activity with increased memory load, whereas brain regions not hypothesised to be involved in WM were unaffected.

Another aspect of WM that has been experimentally manipulated while investigating changes in brain activation with a PET study, is inhibitory control. Jonides, Smith, Marshuetz, Koeppe, and Reuter-Lorenz (1998) devised an item-recognition task and manipulated the recruitment of inhibitory processes using a condition where probes were presented, which matched target items on previous trials. They found that in this condition left lateral prefrontal structures were activated.

The updating process has also been studied using PET (Salmon, Van der, Collette, Delfiore, Maquet, Degueldre, Luxen, & Franck, 1996) by using an adaptation of Morris and Jones' updating task (1990) and comparing this to a simple phonological WM task. The assumption was that the former task would require both the central executive and the phonological loop, but the latter would only involve the phonological loop. Comparing the two tasks, central executive involvement was associated with an increase of regional cerebral blood flow (rCBF) in the right mid-dorsal prefrontal cortex, the left middle frontal regions, the right frontal pole the right inferior parietal and angular gyri and the left supramarginal gyrus. The authors also found activation in cuneus/precuneus and superior occipital gyri bilateraly, the right thalamus and the cerebellum. A limitation of this study was that the tasks required recognition memory and not recall, which might employ differential strategies, visuo-spatial compared to verbal respectively (Van der Linden, Collette, Salmon, Delfiore, Degueldre, Luxen, & Franck, 1999). In a later study, the authors (Van der Linden et al., 1999) used a serial recall procedure to prevent participants using visuo-spatial strategies. They also modified the task by decreasing the memory load to four items instead of six items load of the previous study. This was to prevent the central executive from being recruited to perform the storage function (in order to increase the number of items stored) as well as in the updating function. They found increased activation in the left frontopolar cortex extending to the left middle frontal cortex during the updating task, suggesting an involvement of this area in the updating process of the central executive.

In a PET study investigating similarities in brain activity during various memory tasks (tapping WM, episodic memory and semantic memory), Nyberg, Marklund, Persson, Cabeza, Forkstam, Petersson, and Ingvar (2003) analysed some of the existing evidence for memory-related activity in the brain. Updating and maintaining the contents of WM has been related to increased activity in the mid-ventrolateral prefrontal cortex (Milner, Petrides, & Smith M.L., 1985; Petrides, 1994b; Fletcher & Henson, 2001). In relation to this, it has been suggested that WM processes contribute to LTM tasks (Wagner, 2002) and that mid-ventrolateral prefrontal cortex mediates the active encoding and retrieval of information, and has therefore a general role in memory (Owen, Lee, & Williams, 2000). Cognitive operations requiring the active selection and monitoring of material held in WM involve mid-dorsolateral prefrontal cortex (D'Esposito, Aguirre G.K., Zarahn E., Ballard D., Shin R.K., & Lease J., 1998; Fletcher & Henson, 2001; D'Esposito, 2001), which seems also to be critical in evaluating information attended to (Christoff & Gabrieli, 2000).

Neuropsychologially, D'Esposito and Postle (1999) have shown that the effect of prefrontal lesion on WM performance depends on the complexity of the task: patients with prefrontal lesions exhibited intact performance on simple WM span tasks but their performance was impaired on WM tasks that required attentional inhibition or selection processes. It would seem, therefore, that the involvement of prefrontal cortex in WM tasks critically depends on what (executive) processes they tax.

A study using latent variable analysis (Miyake, Friedman, Emerson, Witzki, & Howerter, 2000) investigated the separability of three executive functions (i.e. mental set shifting; updating and monitoring of information; inhibition of prepotent responses) and their roles in complex "frontal lobe" tasks (Wisconsin Card Sorting Test –WCST; Tower of Hanoi –TOH; Random Number Generation -RNG; operation span; dual tasking). The three executive functions were found to be moderately correlated but clearly separable and they were found to contribute differentially to performance on the complex executive tasks. The WCST is related to shifting; the TOH is related to Inhibiton; the RNG is related to Inhibition and Updating; the Operation Span is related to Updating; and the Dual Task is not related to any of the three executive functions).

Collette, Van der Linden, Laureys, Defiore, Degueldre, Luxen and Salmon (2005) used PET to examine the cerebral areas associated with updating, shifting and inhibition. All conditions consisted of an experimental task and of a matched control task. For the updating task they used three conditions: visually presented consonants (an adapted version of the updating task (Morris & Jones, 1990; Van der Linden, Bredart, & Beerten, 1994)), visually presented words (mono-, bi- and trisyllabic words from six semantic categories) and sounds presented through earphones (low-, medium- and high-pitch tones). For the shifting task there were three conditions: arithmetic operations (using numbers from 10 to 99 and requiring to add/ subtract 3), verbal categorisations (using number-letter pairs and requiring processing of only one of the two categories), and visual categorisations (using Navon (1977) figures[167], and requiring to process at the global/local level). For the inhibition task they used the Stroop task (1935) (using 12 words printed in different inks, half of the words being colour-names and half of the words representing concrete items); and the antisaccade task using a visual cue and a target stimulus on the same or opposite sides of a computer screen (Roberts, Hager, & Heron, 1994). The authors found that all tasks activated the right intraparietal sulcus, the left superior parietal gyrus and the left lateral prefrontal cortex, which suggests that these areas play a general role in executive functioning. More specifically, the authors found that the right intraparietal sulcus is involved in selective attention to relevant information and the suppression of irrelevant information. The left superior parietal region plays a role in amodal switching and integration processes. The authors also suggest that the role played by the lateral prefrontal cortex is one of monitoring and the temporal organization of cognitive processes needed to carry out ongoing tasks. Collette et al. (Collette, Van der Linden, Laureys, Delfiore, Degueldre, Luxen, & Salmon, 2005) also found that specific prefrontal areas were associated with each executive process: updating was found to depend upon a bilateral neural network including anterior and posterior cerebral areas; shifting was associated with parietal and left middle and inferior frontal gyri; inhibition was associated with a priori activation of parietal areas, left middle frontal gyrus and inferior frontal cortex bilaterally.

[167] Navon figures consist of a global form (e.g. a circle) which is composed by smaller local forms (e.g. triangles). According to Navon (1977) global figures are perceived before local figures.

These are all common cerebral areas already found in the conjunction analysis of the three executive processes. Interaction analyses showed that the right orbitofrontal gyrus (BA 11) and the right middle/superior frontal gyrus (BA 10) are more closely associated with inhibitory functioning than with the other two executive processes.

O'Reilly and Munakata (2000) investigated updating at neural level and argued that the prefrontal cortex is responsible for rapid updates of the contents of WM. Dopamine has been suggested to be important for the regulation of the frontal memory system (Cohen & O'Reilly, 1996; O'Reilly, Braver, & Cohen, 1999) because of its capacity to intensify both afferent excitatory and inhibitory signals (Chiodo & Berger, 1986; Penit-Soria, Audinat, & Crepel, 1987). Cohen and O'Reilly (1996) suggested that the active regulation of the process of updating representations in the frontal cortex could happen via the midbrain nuclei sending dopamine to the ventral tegmental area. Dopamine might enhance the strength of afferent connections into the frontal cortex from other brain areas for rapid updating. O'Reilly and Munakata (2000) suggested that dopamine could work as a dynamic gating mechanism allowing, when it is firing, a rapid updating of representations. Without dopamine, the "gate" into WM would be closed, allowing robust maintenance. This dynamic regulation system for switching between maintenance and updating would serve the different needs of the memory system well, where sometimes a representation needs to be robust against new inputs and at other times an updating of current representation is required.

The involvement of the prefrontal lobes in separable executive functions raises the question of what role they could play in complex cognitive functions (e.g. complex mental calculation, reading comprehension) that require the use of some of the above mentioned executive processes (e.g. updating, switching, inhibition). In the following section the available evidence for the involvement of the frontal lobes in one such complex function, numerical processing, will be discussed.

5.1.2. Numerical processes and the frontal lobe

The term "acalculia" was first introduced by Henschen (1925) to refer to the impairments in mathematical skills in brain damaged patients. In fact, an impairment of number processing and calculation abilities is often associated with brain damage. This in most cases derives from an impairment of more general abilities that are required for performing arithmetical tasks (e.g. language, attention, memory, visuo-spatial ability). According to the distinction made by Berger (1926) this kind of dyscalculia would be labelled "secondary" dyscalculia as opposed to "primary" dyscalculia, involving a primary defect in computational abilities and often the disruption of specific mechanisms (Boller & Grafman, 1983). For example, Boller and Grafman (1985; Grafman, 1988) have suggested that calculation abilities can be disrupted as a consequence of: an inability to understand the meaning of the number names; visuo-spatial deficits interfering with the spatial arrangement of numbers; an inability to recall arithmetical facts and use them in the correct way; or deficits in mathematical thinking and understanding underlying operations.

Dehaene and Cohen (1997) referred to a category-specific impairment of the semantic representation and manipulation of numerical quantities. Patients presenting with this impairment, often have other deficits that can cluster into what has been called Gerstmann's syndrome that includes agraphia, finger agnosia and difficulties in distinguishing left and right (Gerstmann, 1940; Benton, 1992).

According to the cognitive model of number processing and calculation suggested by McCloskey et al. (McCloskey & Caramazza, 1987; McCloskey, Aliminosa, & Sokol, 1991), there are two distinct systems The first is a system for number processing, comprising subsystems for comprehension and production of Arabic and verbal number form. The second is and a system for calculation, comprising subsystems for the comprehension of arithmetical signs (+, -, X, :), the retrieval of arithmetical facts (e.g. the multiplication table) and carrying out calculation procedures. According to this model, during number-processing is transformed into an abstract representation that triggers the calculation system and activates speech and writing centres.

5.1.2.1. Neuropsychological studies

In the case of brain pathology, the different subsystems can dissociate. Errors in calculation observed in brain damaged patients can be the consequence of incorrect fact retrieval, mistakes in the use of arithmetical rules and procedural errors (McCloskey et al., 1985). Moreover, Dagenbach and McCloskey (1992) suggest that dissociations between arithmetical facts are the result of selective damage to separate memory networks specific for each operation. Another view came from Dehaene et al. (Dehaene, 1992; Dehaene & Cohen, 1995; 1997) who claimed that in order to understand the processes behind calculation, the different operations had to be analysed separately. The authors did not believe that arithmetical facts were stored in LTM in an abstract format (McCloskey, 1992). According to the triple-code model of numerical processing (Dehaene, 1992), numbers can be represented in the human brain in three different formats: as

Arabic numerals in the Visual Arabic code, as sequences of number words in the Verbal code and as analogical representations of the corresponding magnitude in the Magnitude code. According to Dehaene, these three codes serve different functions: the Visual Arabic code serves multi-digit calculation and parity judgements; the Verbal is involved in the retrieval of rote arithmetical facts (i.e. simple addition and multiplication); the Magnitude code serves semantic knowledge about numerical quantities. Since some arithmetical facts (i.e. addition and multiplication) are taught verbally, they are stored as verbal associations; whereas subtraction and division depend on semantic elaboration and the use of strategies (Dehaene & Cohen, 1997; Cohen & Dehaene, 2000). Therefore, difficulties with rote verbal memory accompany difficulties in multiplication and simple addition - these operations would generally be impaired together. There is some neuropsychological data in favour of a verbal representation of some arithmetical facts (Cipolotti & van Harskamp, 2001; Dehaene, Piazza, Pinel, & Cohen, 2003), but at present neuroimaging studies seem to support the idea that there is a specific area of the brain (the horizontal portion of the intraparietal sulcus) involved in all number tasks. This area holds an amodal and language-independent semantic representation of numerical quantity, and this representation can be accessed through both symbolic and non-symbolic codes (Dehaene, Molko, Cohen, & Wilson, 2004).

Cases of primary dyscalculia following brain damage have often been reported following damage to the parieto-occipital areas (Benson & Weir, 1972; Verney, 1984) or damage of the inferior parietal lobe (Warrington, 1982; Takayama, Sugishita, Akiguchi, & Kimura, 1994; Dehaene & Cohen, 1997; van Harskamp & Cipolotti, 2001), but only in two cases following a frontal lesion

(Lucchelli & De Renzi, 1993; Tohgi, Saitoh, Takahashi, Takahashi, Utsugisawa, Yonezawa, Hatano, & Sasaki, 1995). As mentioned above, cases have been found of patients with parietal lesions showing selective impairments of individual arithmetical facts: in some patients multiplication was more impaired than subtraction (Dagenbach & McCloskey, 1992; Lampl, Eshel, Gilad, & Sarova-Pinhas, 1994; Pesenti, Seron, & Van der Linden, 1994; Dehaene & Cohen, 1997; Lee, 2000; Cohen, Dehaene, Chochon, Lehéricy, & Naccache, 2000; van Harskamp & Cipolotti, 2001), in other patients the opposite pattern was present (Dehaene & Cohen, 1997; Delazer & Benke, 1997; van Harskamp & Cipolotti, 2001). Lucchelli and De Renzi (1993) studied a patient who had an infarct of the left anterior cerebral artery with consequent damage to the medial frontal cortex. The patient showed severely impaired execution of calculation procedures (mainly associated with an inability to remember "carry" and "borrow" procedures" and misconceptions of the nature of the requested operation), mildly impaired fact retrieval but intact comprehension of verbal and Arabic numbers and arithmetical signs. Another patient presented with agraphia and primary dyscalculia following a left prefrontal infarction involving the middle frontal gyrus, the upper part of the inferior frontal gyrus and part of the precentral gyrus (Tohgi et al., 1995). He could add and subtract numbers but was unable to carry out multiplications and divisions because of problems in retrieving the multiplication tables and calculation procedures (particularly carrying and borrowing).

As far as secondary dyscalculia is concerned, Ardila and Rosselli (1990; 2002) have proposed a classification according to the defects causing the calculation difficulties, and they distinguish between: aphasic acalculia, alexic acalculia, agraphic acalculia, spatial acalculia, and frontal acalculia, as resulting from linguistic defects (oral or written), spatial deficits, and frontal-type disturbances (particularly preservation, memory, and attention impairments) respectively. Although attempts to classify different kinds of dyscalculia can be helpful, it is important to note that there is a degree of overlap among these subtypes. Furthermore, although arithmetical calculation is a quite complex cognitive function, brain damage can selectively affect a very limited aspect. For example, dissociations have been found between arithmetical procedures and retrieval of computation facts (Warrington, 1982). A selective inability to carry over when performing arithmetical operations was found in a patient with preserved ability to read and write numbers and arithmetical signs and preserved knowledge of arithmetical facts (Benson & Weir, 1972). A selective inability to recall arithmetical facts for multiplication and division was discovered in a patient whose cardinality judgement, recognition of arithmetical signs, written calculation, retrieval of arithmetical facts for addition and subtraction and ability to solve arithmetical problems were preserved (Hittmair-Delazer, Semenza, & Denes, 1994). Furthermore, a double dissociation was found by Dehaene and Cohen (1997) between rote verbal knowledge (e.g. knowledge of the multiplication table) and semantic knowledge of numerical quantities. Also, a specific deficit for monitoring the sequence of operations required by calculation procedures was studied by Semenza et al. (1997) in a patient whose knowledge of arithmetical procedures was intact. Semenza et al. made a distinction between defective knowledge/memory of arithmetical procedures and a "monitoring deficit", illuminating the role of executive functions in calculation. The former deficit is characterized by: consistent and systematic errors; no decrement in performance with the proceeding of the operation; no difficulty in knowing when subsets of the operation are completed; modifications with training; and possible awareness of the specific difficulty. The "monitoring deficit" is characterized by: inconsistent and unsystematic errors; a decrement in performance with the proceeding of the operation; difficulty in ending operations; no effect of training; and a lack of awareness of the accuracy of performance. As far as the categorization of secondary dyscalculias is concerned, Ardila and Rosselli's (2002) conceptualization of frontal acalculia is of particular relevance for this study. According to the authors, patients with prefrontal lobe damage may show difficulties in mental operations, consecutive operations (especially backwards) and multi-step numerical problems. Written operations are a lesser problem, as using pen and pencil helps keep track of the material held in WM. The difficulties shown during calculation can be due to attentional difficulties (leading to non-attendance to the conditions of the task and impulsiveness in answers), perseveration (leading to difficulty in correcting a wrong answer) or an impairment in the use of complex mathematical concepts (resulting in an inability to develop an algorithm for solving a problem). Moreover, patients with frontal lobe pathology often present with difficulties in the use of temporal measures, which may be related to problems in temporal memory and in time concepts observed in this group of patients (Fuster, 1980).

According to Luria, and other researchers one of the most subtle impairments that can be caused by frontal lobe damage, is the inability to solve arithmetic word problems (Luria, 1966; Luria & Tsvetkova, 1967; Lhermitte, Derouesne, & Signoret, 1972; Christensen, 1975; Walsh, 1978). Despite still possessing basic mathematical skills (such as the ability to solve simple arithmetical operations (Christensen, 1975; Walsh, 1978), and to deal with the visuo-spatial organisation of numbers (Luria & Tsvetkova, 1967; Hecaen, 1969)), people with frontal damage may find arithmetical word problem solving difficult (Luria & Tsvetkova, 1967; Fasotti, Ealing, & Bremer, 1992). According to Luria and Tsvetkova (1967), patients with frontal lobe lesions are penalised by their impulsivity, and try to solve the problem according to the first fragment of the word problem to attract their attention: they are therefore unable to formulate a strategy that takes into account all the elements needed to solve the problem. It is therefore the inability to inhibit an initial response that is considered by some authors responsible for the poor performance of this category of patients (Luria & Tsvetkova, 1967; Lhermitte et al., 1972). Another interpretation of this kind of performance comes from Barbizet (1970) who suggests that the difficulty found by frontal patients may be due to a specific memory deficit, which rather than affecting the information relevant to solve the problem, it affects the person's ability to correctly proceed in the solution process. This view is supported by the finding that breaking down the problem into stages and asking for an intermediate solution at each step, improves performance on people with frontal lobe damage.

This approach to the solution of arithmetical word problems is in clear contrast with the approach of patients with posterior lesions (parieto-temporo-occipital) who often look for the information required for the formulation of a strategy to solve the problem, which Luria considers and indicator of the presence of the preliminary orientation stage, one of the essential stages involved in human thinking (Luria, 1973). On the contrary, patients with frontal lesions often fail to investigate the information required to make problem solving possible, and are therefore unable to formulate a plan or devise a strategy (Luria & Tsvetkova, 1967; Christensen, 1975). However, Luria and Tsvetkova (1967) state that these patients often have difficulties in understanding complex attributive (e.g. "The mother gives two apples to the daughter") or comparative sentences (e.g. "Lucy is taller than her sister") as well as transforming them into mathematical operations. Fasotti et al. (1992) have investigated arithmetical word problem solving from an information-processing point of view, in order to identify at what stages of the information processing chain problems arise. The authors investigated the first stage in word problem solving, i.e. the translation of sentences to internal representations, in patients with frontal lobe damage, those with posterior damage and healthy controls. Recognition and a sentence-picture matching tasks were used. The authors found that the stage of sentence encoding was affected in patients with frontal and left posterior damage. The length of the sentence and the amount of information conveyed influenced encoding difficulty. The logical and grammatical complexity of the sentence led to difficulties in encoding where the brain lesion affected language abilities. A limitation of this study is that it failed to explore later stages of word problem solving and possible impairments at these stages.

Other interesting suggestions about the role of the frontal lobe in mental calculation come from the study of calculating prodigies (Pesenti, Seron, Samson, & Duroux, 1999; Pesenti, Zago, Crivello, Mellet, Samson, Duroux, Seron, Mazoyer, & Tzourio-Mazoyer, 2001). Expert calculators are able to solve complex mental calculations quickly and accurately, which, because of their high STM demands, are very challenging for other educated adults. It has been suggested that calculating prodigies are able, through practice, to rapidly encode intermediate results in long-term WM with cues that facilitate efficient retrieval, reducing in this way the demands on STM(Ericsson & Kintsch, 1995). The concept of "long-term WM" was developed by Ericsson and Kintsch (1995) to refer to a WM based on storage in LTM. According to the authors, when performing complex cognitive tasks, people need to access large amount of information. They argue that this is possible because acquired memory skills, specific to each domain of expertise, allow them to store this information in LTM and to keep it directly accessible by means of retrieval cues in STM. Pesenti and colleagues (Pesenti et al., 1999; 2001) studied the calculation abilities of an exceptional calculator, investigating both his basic and exceptional calculation skills. They found that his exceptional expertise was due to various contributing factors: extremely efficient LTM storage and retrieval processes, knowledge of calculation algorithms and good STM capacity (Pesenti et al., 1999). They also investigated the neural bases of his ability using PET during retrieval of arithmetic facts and complex mental calculation, comparing him to a group of non-expert controls (Pesenti et al., 2001). They found that the exceptional calculator used different processes that relied on different brain areas to perform the calculations. In particular he was able to apply automated resolution algorithms and to carefully monitor and control these processes, and he could switch from effortful short-term storage strategies to highly efficient long-term encoding and retrieval strategies. The latter process was sustained by right prefrontal and medial temporal areas.

5.1.2.2. Neuroimaging studies

There is a wealth of neuroimaging studies investigating the neuroanatomical substrates of numerical processing and calculation. Although most of these studies focus on the involvement of the left inferior parietal lobe (in particular the intra-parietal sulcus, IPS) in number tasks, it seems that the frontal lobes, in particular areas of the precentral and inferior prefrontal cortex, are also activated during mental calculation tasks. It has been suggested that the horizontal segment of the IPS (HIPS) is the only region to be consistently activated in the experiments involving number detection and number comparison rather than complex calculation (Naccache & Dehaene, 2001; Pinel, Dehaene, Riviere, & LeBihan, 2001; Eger, Sterzer, Russ, , Giraud, & Kleinschmidt, 2003). Dehaene, Piazza, Pinel and Cohen (2003) tried to clarify the organisation of numerical processes in the parietal lobe, which -as discussed above- has been suggested to be the substrate for the domain-specific representation of quantities, but is also involved in other functions that may have a role in calculation(e.g. attentional, verbal, and spatial). For example, the perisylvian language network reaches to the inferior parietal lobe. The posterior superior parietal lobes are involved in visual attention which may contribute to the visual processing of numbers. Therefore the authors, in order to distinguish between sites activated by non-specific verbal or visual attentional processing and sites activated by the semantic representation of quantities, investigated how the parietal activations reported by various neuroimaging studies related to one other in the cortical space. They proposed the presence of three parietal circuits: a bilateral intraparietal system, with the HIPS as a major site of activation, associated with a domain-specific, or "core", quantity system; a region of the left angular gyrus, connected with other perisylvian areas, involved in the verbal processing of numbers; and a posterior superior parietal system involved in spatial (e.g. for orientation in the mental number line) and non-spatial attention. This account is in line with the triple-code model of number processing (Dehaene, 1992; Dehaene & Cohen, 1995). This predicts similar systems of representation: a nonverbal semantic quantity system, for the representation of size and distance between numbers; a verbal system, for the lexical, phonological and syntactical representation of numerals; and a visual system, for the encoding of numerals as strings of Arabic numerals. It also predicts, in neuropsychological patients, three different types of numerical impairments depending on the site of the lesion: impairment of the numerical domain with intraparietal lesions (Cipolotti, Butterworth, & Denes, 1991; Dehaene & Cohen, 1997; Delazer & Benke, 1997); verbal fact retrieval impairments with lesions of the perisylvian area (Cohen et al., 2000; Duffau, Denvil, Lopes, Gasparini, Cohen, Capelle, & van Effenterre, 2002); and impaired spatial attention on the number line with lesions of the dorsal parietal system (Gobel, Walsh, & Rushworth, 2001; Zorzi, Priftis, & Umiltà, 2002).

Neuroimaging studies have shown that specific parietal, prefrontal and cingulate areas are systematically activated during mental calculation (Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999; Chochon, Cohen, van de Moortele, & Dehaene, 1999; Pesenti, Thioux, Seron, & De, 2000; Lee, 2000; Gruber, Indefrey, Steinmetz, & Kleinschmidt, 2001; Zago, Pesenti, Mellet, Crivello, Mazoyer, & Tzourio-Mazoyer, 2001; Simon, Mangin, Cohen, Le Bihan, & Dehaene, 2002). Dehaene et al. (2004) argued that the HIPS plays a key role in basic quantity representation and manipulation, and that the prefrontal areas might be involved in the management of consecutive operations in WM. Pesenti et al. (2000) used PET to localize the neuroanatomical substrates of three basic numerical processes: Arabic numeral processing, numerical magnitude comparison, and retrieval of simple addition facts. Their results showed that addition activated left intraparietal and superior parietal areas, the precentral gyrus, the orbito-frontal areas, and the anterior insula in the right hemisphere. The authors suggest that this involvement might have to do with the motivational-emotional aspects of learning. In an fMRI study mapping brain activity during arithmetical tasks and control tasks involving a similar load on language, attention, memory and visuo-spatial abilities, an increase of activity in the left inferior frontal areas (thought to subserve lingusistic and WM functions) was found during complex calculation tasks that involved meaningful operations on WM representations of letters or numbers and that required manipulation of items held in WM (Gruber et al., 2001). These results led the authors to suggest that the observed activations of the inferior frontal areas were due to additional recruitment of WM.

In conclusion, several neuropsychological and neuroimaging studies have shown an involvement of the prefrontal lobes, particularly the inferior areas, in calculation. Apart from a few exceptions (Lucchelli & De Renzi, 1993; Tohgi et al., 1995) this involvement is thought to be attributable to the WM and executive functions located in the frontal lobes and required for complex mental calculation.

To date no study has been conducted which looks at the numerical abilities of a group of patients with frontal lesions. It is interesting to investigate this bearing in mind the concept of frontal dyscalculia described above (Ardila & Rosselli, 2002).

5.1.3. Aims of the study

The first aim of this preliminary study is to investigate the processes studied in the previous chapters, in people with a frontal lobe lesion, and to ascertain whether frontal lobe damage selectively affects specific components of WM. WM is investigated studying distinct aspects of the CE: its maintenance processes and its control processes. People with a frontal lobe lesion are expected to have difficulties in planning, regulating and controlling activities (Luria, 1966; 1969; Shallice, 1982). These skills are thought to be required for performance on the updating task, and in particular for the inhibition of irrelevant information. Therefore, poor performance in inhibiting irrelevant information (i.e. in using control processes) is expected in people with a frontal lobe lesion compared to both a group with more posterior damage (temporo-occipital) and a group of healthy controls. No difference is expected in recall performance (i.e. maintenance processes), in accordance with the suggestions by Baddeley (1986) concerning dysexecutive frontal lobe syndrome. It is important to note that in the present study, those in the frontal lobe group did not show signs of dysexecutive syndrome. This will be considered when interpreting the results, but the updating task, with its increased loading on control processes, may be a sensitive enough instrument to detect more subtle difficulties in planning and control processes, not evident on standard tests.

Moreover, the predictions are that performance on both recall and inhibition of irrelevant information will be more affected by load on control processes in people with frontal lobe lesion compared with their controls (both with posterior brain damage and healthy). This is consistent with the idea that in patients with frontal lobe damage, planning and control processes are impaired (Luria, 1966; 1969; Shallice, 1982) and therefore these patients are expected to be more sensitive to demands on control processes that are not challenging for people without a frontal lobe damage.

Differences are also expected in the digit span backwards task, with lower performance by the group with frontal lobe damage compared with the other two groups. No other differences between the groups are expected in the span tests, consistent with the idea that only control processes are affected by frontal lobe lesions.

A further aim of this preliminary study is to investigate whether there are any differences between patients with frontal lobe damage and controls in performance on numerical and calculation tasks. In order to do so, the same measures of numerical and calculation processing are used as in the previous chapter, providing a screening of various different numerical and calculation abilities. The predictions are that participants with frontal lobe damage will perform poorly in complex mental calculation compared to controls. This is expected because complex mental calculation requires: holding and manipulating numbers in STM; the application of the appropriate algorithm, involving various steps to be followed in the appropriate sequence; the retrieval and temporary storage of intermediate results that will have to be forgotten after being used; and the application of arithmetical rules. This complex process is thought to require attentional control and WM processes (Baddeley, 1986), which are expected to be impaired in people with frontal lobe damage. This prediction is also consistent with the concept of "frontal acalculia", proposed by Ardila and Rosselli (2002) to describe difficulties in mental operations, consecutive operations (especially backwards) and multi-step numerical problems shown by patients with prefrontal lobe damage.

Moreover, it is predicted that the differences between frontal lobe patients and their controls will be more evident in calculation tasks that are more taxing on control processes (e.g. requiring the use or more carryings and borrowings).

However, assuming that control processes are impaired in people with frontal lobe damage, it is expected that this group will find it harder to perform operations that are simple for controls with a posterior damage and healthy controls. A further prediction is that participants with frontal lobe damage will perform more poorly in the transcoding tasks. In particular, due to a failure of control mechanism they are expected to produce intrusions of the source code in the target code, similarly to what has been found in DAT (Kessler & Kalbe, 1996). No differences are expected between groups in the other tasks.

A final aim of this preliminary study is to investigate the relationship between numerical and calculation impairments in frontal lobe patients and the functioning of WM, and if this relationship is attributable to certain components of WM more than to others. In particular, the prediction is that this group of patients will have a general problem in monitoring arithmetical procedures, possibly an inability to update relevant information and inhibit information no longer useful at different stages of calculation. According to this idea the calculation system will be affected earlier than others by this WM impairment because of the greater load on executive functions and the higher demand of monitoring it requires. If, as proposed, the difficulty with calculation in this group is due to a deficit in control processes, this is likely to produce a varied pattern of errors at different stages of the procedure (Semenza et al., 1997).

5.2. Method

5.2.1. Participants

Forty individuals participated in this study. Twenty were patients (fourteen females, five males) recruited through the CTO Hospital in Turin (Italy). Nine of them had undergone surgery for an aneurism of the Anterior Communicating Artery (ACoA), and therefore had a lesion of the frontal lobe (group F). Eleven were reported to have an Artero-venous malformation (AVM) involving the temporo-occipital lobe (group TOC). An inclusion criterion was a lesion in the region of interest, confirmed by neuroimaging examination. Exclusion criteria for the study were current or past psychiatric problems; additional brain lesions in extrafrontal areas; and sensorial problems which could interfere with the administration of tests. Table 5.1 illustrates age and education of participants in the three groups. As the number of participants in each group is very small and the two clinical groups have different age and education, this study is simply a preliminary one that should serve as an indication of whether further investigate similar groups in future research on WM.

Table 5. 1: Participants' age and education

	Mean (Standard Deviation)		
	F (N=9)	TO (N=11)	C (N=20)
Age	58.8 (13.77)	41.1 (15.83)	49.1 (18.17)
Education	7.8 (4.55)	11.1 (2.95)	9.4 (3.63)
Male: Female Ratio	3:6	4:7	7:13

5.2.2. Neuropsychological screening

As a selection criterion, participants were required to be within the normal range in the Raven Progressive Coloured Matrices (Raven, 1985). Participants were also required to have a verbal digit span forward o at least three digits and backwards at least two digits (Wechsler, 1997). This limitation was necessary to ensure effective administration of the WM task (i.e. making sure that they would understand the instructions and would not perform at floor level). Table 5.2 illustrates performance in the screening tasks in the three groups.

Table 5. 2: Participants' description

	Mean (Standard Deviation)	
	F (N=9)	**TO** (N=11)
RCPM	28.8 (5.97)	33.2 (1.40)
Digit span forward	5.4 (1.59)	5.6 (6.80)
Digit span backwards	3.6 (1.33)	4.4 (0.67)

5.2.3. Experimental Tasks

The administration of the tests was divided into two parts for each individual participant, each lasting for one hour with a one-week interval between the two. This was to prevent excessive fatigue of the participants, and the repetition of stimuli within the same session.

The tasks administered were the same as in the study on DAT patients in Chapter 4, with the difference that the items in the Transcoding Tasks, Arithmetical Facts, and Complex Mental Calculation were presented on individual sheets of paper and not on a computer screen. This was due to technical problems in the facilities where the patients were tested.

5.2.3.1. Working Memory Tasks

SPAN TESTS

The same stimuli and procedures were used as in the study on healthy participants (see Chapter 2).

UPDATING TASK

The same stimuli were used as with healthy participants (see Chapter 2). The procedure was the same, except that the stimuli were not pre-recorded, but read by the experimenter at a speed of one word per second.

5.2.3.2. Numerical Tasks

The numerical tasks consisted of: reading written Arabic numerals; writing Arabic numerals to dictation; transcoding from Arabic numerals to written verbal numbers and vice versa; reading written verbal numerals; writing verbal numerals to dictation; and writing words to dictation (as a control for the previous test). These tests were chosen both to check basic numerical abilities (e.g. comprehension of numerals and comparison of magnitudes), and to evaluate performance on tasks involving inhibition of irrelevant code (Kessler & Kalbe, 1996; Thioux et al., 1999).

WRITING NUMERALS

Twelve numbers were presented verbally by the examiner serially. The participant was required to write them in Arabic format or in Verbal format on a piece of paper. The stimuli were the same in the two tasks and were presented in different sessions.

READING NUMERALS AND TRANSCODING TASKS

- *Arabic to Verbal:*

Twenty written Arabic numerals were visually presented, one per individual sheet of paper. The participant was asked to read them aloud and write them in verbal formats, one by one. The stimuli were presented until the participants finished their response (for a description of stimuli see Appendix 1).

- *Verbal to Arabic:*

The same numbers were presented with the same procedure but as written words (e.g. ONE, THIRTEEN). The participants were asked to read them aloud and write them in Arabic format.

5.2.3.3. Calculation Tasks

ARITHMETICAL FACTS

Thirtytwo problems (ten additions, ten subtractions, twelve multiplications) were visually presented, one per individual sheet of paper. The problems were simple arithmetical facts and both operands were one-digit (for a description of stimuli see Appendix 1). The participant was asked to answer verbally as quickly and accurately as possible.

JACKSON & WARRINGTON TEST

The stimuli from the Jackson & Warrington (1986) test were used with the same procedure as with DAT patients (see Chapter 4).

COMPLEX MENTAL CALCULATION

The participant was presented with the same stimuli and conditions used with DAT patients (see Chapter 4). The procedure was only different in that the stimuli were presented by the researcher on individual sheets of paper.

In both the numerical and the calculation tasks the percentage of hits (correct answers) was considered.

5.3. Results

5.3.1. Working Memory Tasks

5.3.1.1. Span Tests

SPAN FORWARD

A mixed 3X3X2 ANOVA was conducted in order to investigate differences between groups in the span tests. The analysis compared the recall of items of different lengths (bi-syllabic items or 3/5 syllables items) and of different categories (i.e. numbers, objects and animals, and proper names). The between-subjects independent variable was GROUP with three levels (F, TO, and C). The within-subjects independent variables were STIMULUS with three levels (NUMBER, when the stimulus to recall was a number; NOUN, when the stimulus to recall was a name of object or animal; PROPER NAME, when the stimulus to recall was a proper name), and LENGTH with two levels (2-SYLL and 3/5-SYLL). The dependent variable was the number of items correctly recalled in the correct order.

Bonferroni correction was used when multiple comparisons were performed on the data, and all the significance values reported include this correction where necessary.

No significant main effect of GROUP was found[168]. The main effect of STIMULUS is statistically significant [$F(2,74) = 21.99$; $p<0.001$], and it was further investigated by conducting a Paired Samples t-test comparing each of the three levels of the variable with the others. Figure 5.1 shows that when required to recall numbers the performance is significantly better than with both nouns [$t(39) = 4.71$; $p<0.005$], and proper names [$t(39) = 5.95$; $p<0.005$][169].

[168] [$F(2,37) = 3.16$; $p>0.05$]
[169] The latter two conditions did not significantly differ one from the other [$t(39) = 2.15$; $p>0.05$].

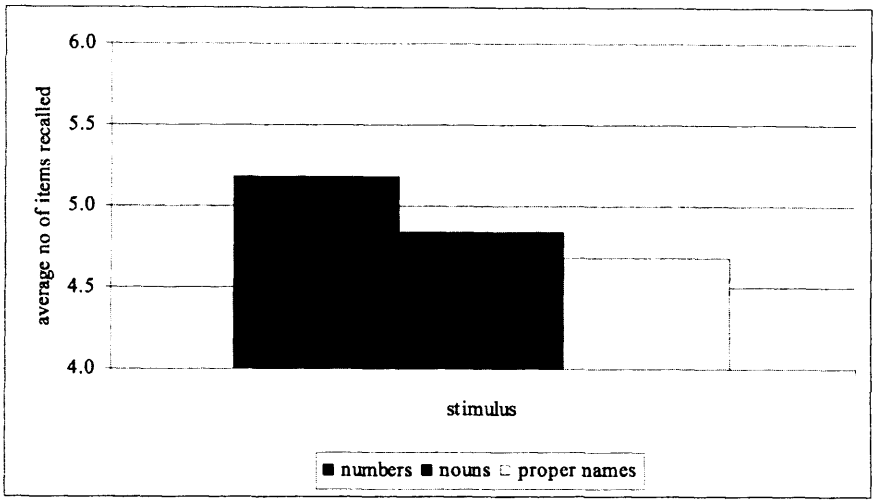

Figure 5. 1: Span tests - main effect of STIMULUS

The main effect of LENGTH is significant [$F(1,37) = 149.52$; $p<0.001$], due to performance with bi-syllabic items being better than when longer items were recalled. The interaction STIMULUS X LENGTH is significant [$F(2,74) = 10.89$; $p<0.001$]. A Paired Samples t-test was conducted comparing each level of stimulus with the other at each level of length. Figure 5.2 illustrates that the only condition where the difference between levels of stimulus is significant is with bi-syllabic items, with the digit span being significantly larger than for nouns [$t(39) = 6.98$; $p<0.01$] and proper names [$t(39) = 6.58$; $p<0.01$][170].

[170] The difference between 2-SYLL NOUN and 2-SYLL PROPER NAME, was not significant [$t(39) = 1.42$; $p>0.05$], nor it was the difference between any of the levels of STIMULUS with 3/5-SYLL LENGTH (3/5-SYLL NUMBER vs 3/5-SYLL NOUN [$t(39) = -1.00$; $p>0.05$], 3/5-SYLL NUMBER vs 3/5-SYLL PROPER NAME [$t(39) = 0.00$; $p>0.05$], 3/5-SYLL NOUN vs 3/5-SYLL PROPER NAME [$t(39) = 1.40$; $p>0.05$].

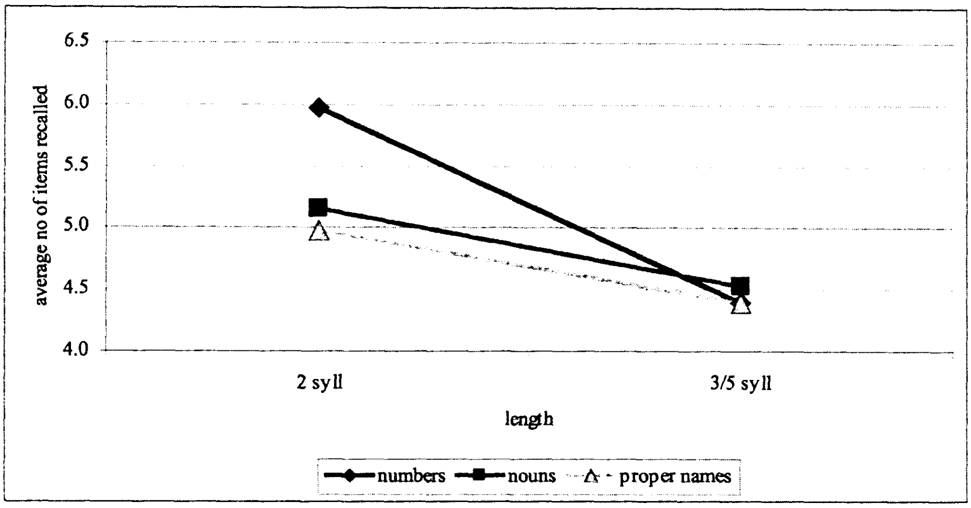

Figure 5. 2: Span tests - interaction STIMULUS X LENGTH

Stimulus and length also interact with group: the interaction STIMULUS X LENGTH X GROUP is significant [F(4,74) = 3.52; p<0.02][171]. In order to investigate this interaction, the same analysis as above was conducted in each group. Figure 5.3 illustrates that, with bi-syllabic items, only the group of healthy controls' digit span is significantly larger than with nouns [t(19) = 5.14; p<0.01] and proper names [t(19) = 6.73; p<0.01]. In the other groups none of the levels differ from any of the others[172].

[171] No significant interactions were found for STIMULUS X GROUP [F(4,74) = 1.26; p>0.05], LENGTH X GROUP [F(2,37) = 0.07; p>0.05]

[172] in F group: 2-SYLL NUMBER vs. 2-SYLL NOUN [t(8) = 3.50; p>0.05]; 2-SYLL NOUN vs. 2-SYLL PROPER NAME [t(8) = -0.36; p>0.05]; 2-SYLL NUMBER vs. 2-SYLL PROPER NAME [t(8) = 1.79; p>0.05]; 3/5-SYLL NUMBER vs. 3/5-SYLL NOUN [t(8) = 2.53; p>0.05]; 3/5-SYLL NOUN vs. 3/5-SYLL PROPER NAME [t(8) = 1.51; p>0.05]; 3/5-SYLL NUMBER vs. 3/5-SYLL PROPER NAME [t(8) = 2.83; p>0.05]; in TO group: 2-SYLL NUMBER vs. 2-SYLL NOUN [t(10) = 3.13; p>0.05]; 2-SYLL NOUN vs. 2-SYLL PROPER NAME [t(10) = 0.43; p>0.05]; 2-SYLL NUMBER vs. 2-SYLL PROPER NAME [t(10) = 2.67; p>0.05]; 3/5-SYLL NUMBER vs. 3/5-SYLL NOUN [t(10) = -1.79; p>0.05]; 3/5-SYLL NOUN vs. 3/5-SYLL PROPER NAME [t(10) = 2.89; p>0.05]; 3/5-SYLL NUMBER vs. 3/5-SYLL PROPER NAME [t(10) = 0.56; p>0.05].

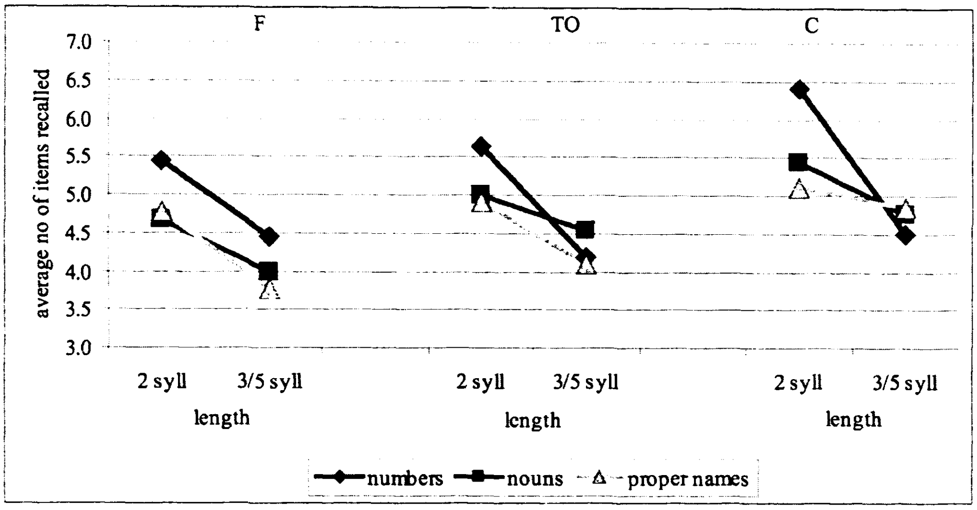

Figure 5. 3: Span tests - interaction STIMULUS X LENGTH X GROUP

DIGIT SPAN BACKWARDS

A one-way between-subjects ANOVA was conducted to compare performance on digit span backwards in the three groups. The between-subjects independent variable was GROUP with three levels (F, TO, and C) and the dependent variable was the number of items recalled by participants in the digit span backwards test.

The results show a significant main effect of GROUP [$F(2,37) = 6.66$; $p<0.005$]. A Tukey's post-hoc test indicates that this difference is due to the F group performing significantly below the C group. As illustrated in Figure 5.4, the other groups do not differ.

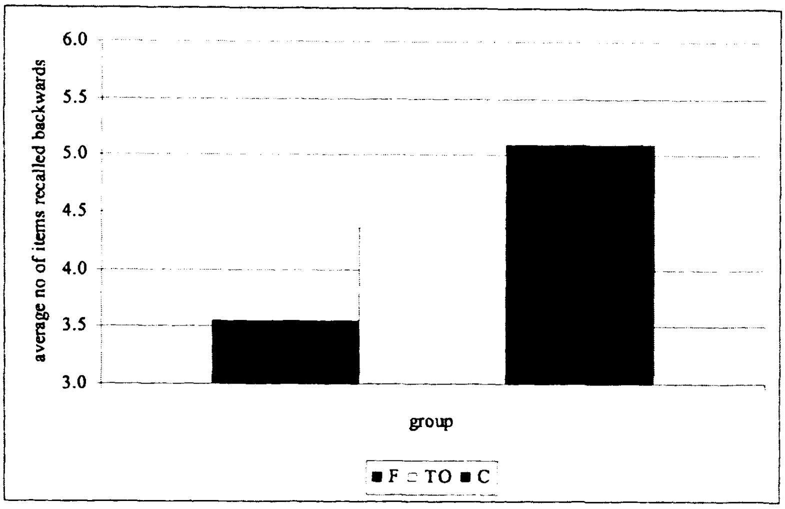

Figure 5. 4: Digit Span backwards - main effect of GROUP

5.3.1.2. Updating Task

In the Updating task, the group with frontal lesions (F), the group with temporo-occipital lesions (TO), and the group of healthy controls (C) were compared. Separate analyses were performed in order to investigate recall performance (i.e. the percentage of correct recall) and the production of errors. These included: intrusion of items from the same list; intrusion of items presented in a previous list; the production of items invented by the participant; and omissions. These were measured as the percentage of items incorrectly recalled (or not recalled, in the case of omissions) from the total number of responses.

Bonferroni correction was used when multiple comparisons were performed on the data, and all the significance values reported include this correction where necessary.

CORRECT RECALL

A 3x2x4x2 mixed design ANOVA was conducted to assess differences in recall performance between the three groups (F, TO, and C) across conditions. The between-subjects factor was GROUP with three levels (F, TO and C). The within-subjects factors were: STIMULUS with two levels (NOUN and NUMBER), RECALL with four levels (R1, R2, R3, R4), and INHIBITION with two levels (LI and HI). The dependent variable was the percentage of correctly recalled items.

The analysis reveals a significant main effect of GROUP [$F(2,37) = 15.34$, $p<0.001$]. A Tukey's post-hoc analysis reveals that this is due to the F group performing significantly worse than both TO [$p<0.001$] and C [$p<0.001$][173] groups, as illustrated in Figure 5.5.

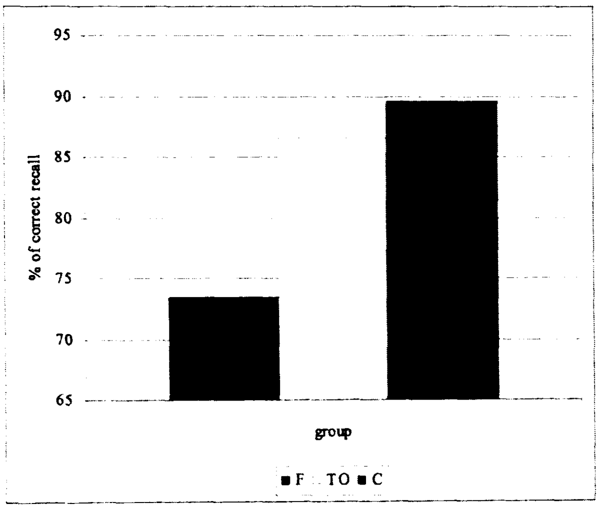

Figure 5. 5: Updating task - Correct recall -main effect of GROUP

The main effect of INHIBITION is significant [$F(1,37) = 113.02$, $p<0.001$], and it is explained by poorer performance on recall when the load on control processes is higher (HI)compared to when the load on control processes is lower (LI).

[173] The TO group instead did not differ from the control group [$p>0.05$].

The main effect of RECALL is significant [$F(2,77) = 107.67$, $p<0.001$], and a polynomial contrast confirms that this factor is better accounted for by a quadratic[174] decrease [$F(1,37) = 35.10$; $p<.0.001$], as illustrated in Figure 5.6.

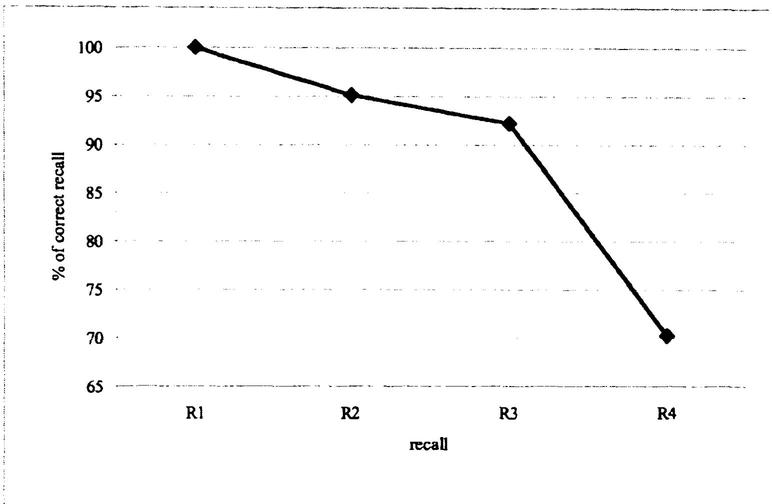

Figure 5. 6: Updating task - Correct recall -main effect of RECALL

A significant main effect of STIMULUS [$F(1,37) = 17.12$, $p<0.001$] is also evident, and this is characterised by recall performance with numbers being significantly below performance with nouns.

The interaction RECALL X GROUP is significant [$F(4,77) = 5.32$, $p < 0.002$]. A between-subjects ANOVA was performed for each level of recall, in order to investigate the interaction. Figure 5.7 illustrates that when there is only one item to recall there is no difference between groups[175]. However, when the items to recall are greater than one, the groups perform significantly differently (with R2 [$F(2,37)= 14.79$; $p <0.001$], R3 [$F(2,37)= 10.65$; $p <0.001$], and R4 [$F(2,37)= 8.04$; $p <0.002$]). A Tukey's post-hoc test shows that these differences are due to the F group performing below the other two groups ($p<0.001$).

[174] A linear [$F(1,37) = 170.25$; $p<.0.001$] and cubic [$F(1,37) = 39.70$; $p<.0.001$] decrease were also found to be significant

[175] [n.s.: Could not compute the difference since all scores were equivalent]

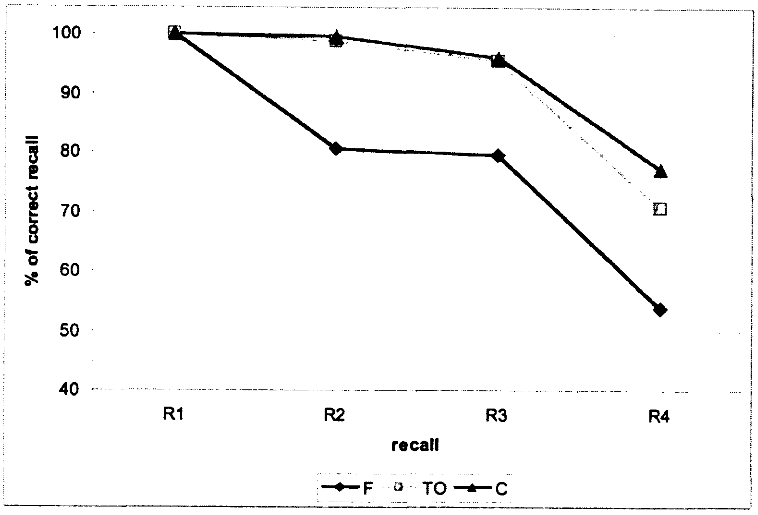

Figure 5. 7: Updating task - Correct recall -interaction RECALL X GROUP

The interaction INHIBITION X RECALL is significant [$F(2,68) = 62.27$, $p < 0.001$]. A Paired Samples t-test was conducted for each level of recall, comparing the performance on the different levels of inhibition. Figure 5.8 illustrates that the difference between low and high inhibition is not significant when the task requires the recall of one or two items[176], but is significant at the other two levels: with R3 [$t(39)= 4.69$, $p<.005$], and R4 [$t(39)= 11.74$, $p<.005$].

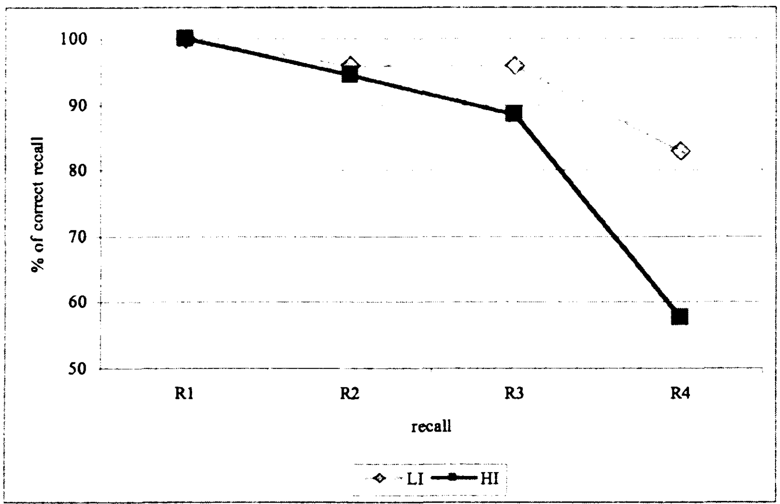

Figure 5. 8: Updating task - Correct recall -interaction INHIBITION X RECALL

[176] (R1) [n.s.: Could not compute the difference since all scores were equivalent], (R2) [$t(39)= 1.96$, $p>0.05$]

Recall also interacts with stimulus: the interaction RECALL X STIMULUS is significant [$F(2,69) = 18.62$, $p < 0.001$][177]. A Paired Samples t-test was conducted for each level of recall, comparing the performance at the different levels of stimulus. Figure 5.9 illustrates that the difference between nouns and numbers is only significant when the task requires to recall four items (R4) [$t(39)= 5.52$, $p<0.005$], and it is not significant at the other levels[178].

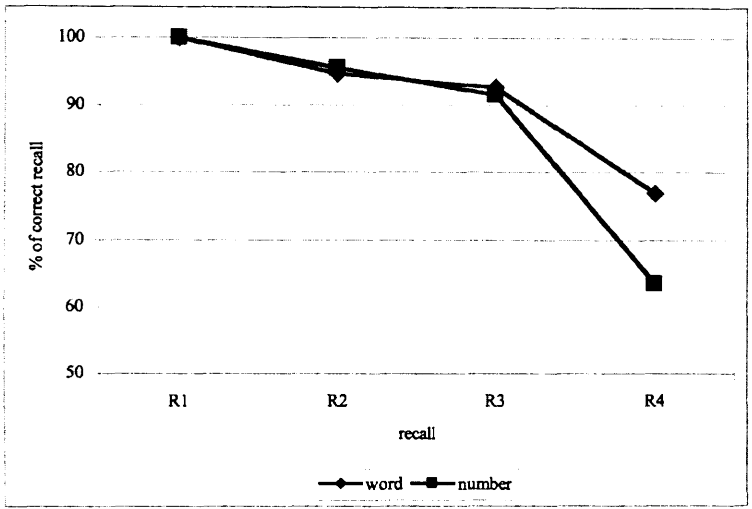

Figure 5. 9: Updating task - Correct recall -interaction RECALL X STIMULUS

SAME LIST INTRUSION ERRORS

A 3x2x4x2 mixed design ANOVA was conducted to assess differences between the three groups (F, TO, and C) across conditions in the production of intrusion errors of words from the same list. The independent variables were the same as in the previous analysis, and the dependent variable was the percentage of intrusions from the same list (as a proportion of the total number of responses).

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177 The other interactions (INHIBITION X GROUP [$F(2,37) = 0.04$, $p>0.05$], STIMULUS X GROUP [$F(2,37) = 0.74$, $p>0.05$]; INHIBITION X RECALL X GROUP [$F(4,68) = 1.73$, $p>0.05$], INHIBITION X STIMULUS [$F(1,37) = 2.17$, $p>0.05$]; INHIBITION X STIMULUS X GROUP [$F(2,37) = 0.63$, $p>0.05$]; RECALL X STIMULUS X GROUP [$F(4,69) = 1.61$, $p>0.05$]; INHIBITION X RECALL X STIMULUS [$F(2,91) = 0.41$, $p>0.05$] were not significant.

178 R1 [n.s.: Could not compute the difference since all scores were equivalent], R2 [$t(39)= -0.57$, $p>0.05$], and R3 [$t(39)= 0.72$, $p>0.05$]

The main effect of GROUP is significant [$F(2,37) = 16.34$, $p<0.001$]. A Tukey's post-hoc analysis reveals that the difference between groups is due to the F group performing significantly below both TO [$p<0.001$] and C [$p<0.001$][179] groups, as illustrated in Figure 5.10.

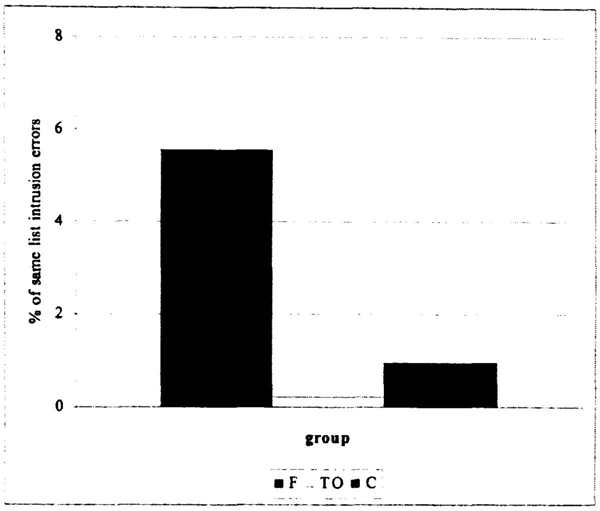

Figure 5. 10: Updating task - Same list intrusion errors - main effect of GROUP

The main effect of INHIBITION is significant [$F(1,37) = 6.91$, $p<0.02$], due to a higher percentage of intrusions from the same list being produced when the load on control processes is higher (HI)compared to when it is lower (i.e. with LI).

RECALL is a significant main effect [$F(2,80) = 8.92$, $p<0.001$]. A polynomial contrast confirms that this factor shows a significantly linear increase [$F(1,37) = 24.94$; $p<.0.001$]. As the number of items to be recalled increases, increasingly more same list intrusion errors are produced, as illustrated in Figure 5.11.

[179] The TO group instead did not differ from the control group [$p>0.05$].

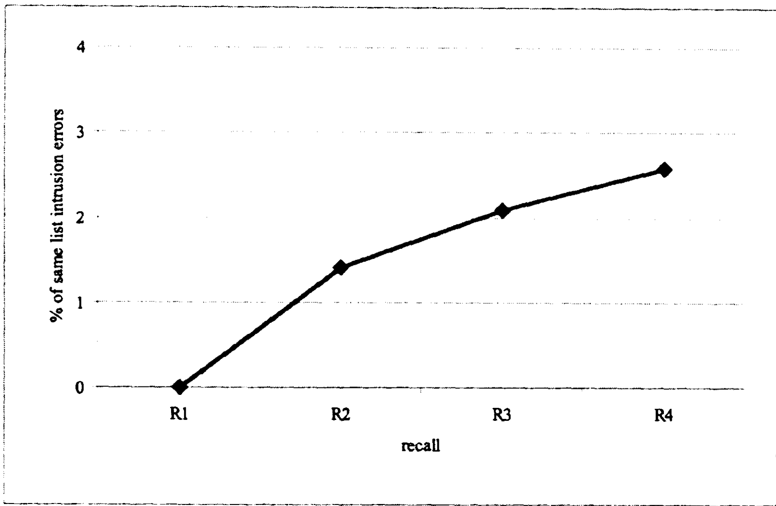

Figure 5. 11: Updating task - Same list intrusion errors - main effect of RECALL

The main effect of STIMULUS is significant [F(1,37) = 8.97, p<0.01], due to a higher percentage of intrusions from the same list errors being produced with words than with numbers.

The interaction RECALL X GROUP is significant [F(4,80) = 5.72, p <0.001]. A between-subjects ANOVA was performed for each level of recall, in order to further investigate the interaction. Figure 5.12 shows that when there is only one item to recall there is no difference[180] between groups in the production of same list intrusion errors. However, when the items to recall are more than one, the groups perform significantly differently (with R2 [F(2,37)= 8.08; p <0.002], R3 [F(2,37)= 17.37; p <0.001], and R4 [F(2,37)= 7.56; p <0.005]). A Tukey's post-hoc test shows that these differences are due to the F group performing significantly below the other two groups with R2 [p<0.01 compared to TO; p<0.005 compared to C], R3 [p<0.001 compared to both the other groups], and R4 [p<0.005 compared to TO; p<0.02 compared to C]. The TO and C groups do not significantly differ from one another at any level of recall.

[180] [n.s.: Could not compute the difference since all scores were equivalent]

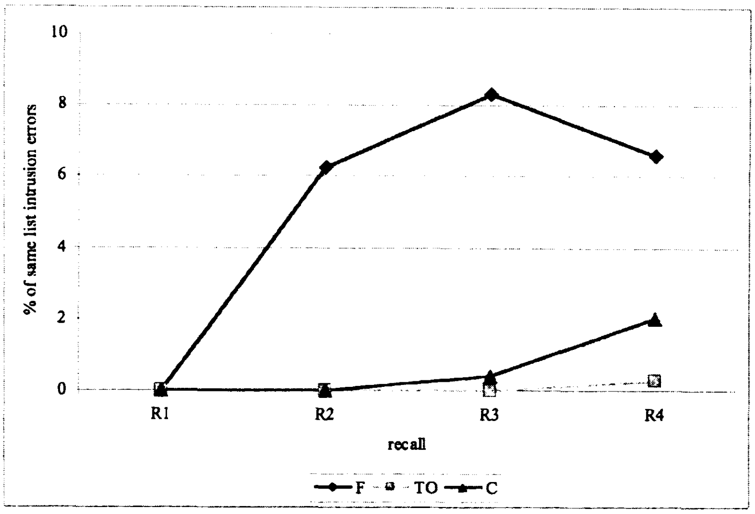

Figure 5. 12: Updating task - Same list intrusion errors - interaction RECALL X GROUP

Group also interacts with stimulus: the interaction STIMULUS X GROUP is significant [$F(2,37) = 4.65$, $p<0.02$]. To analyse this interaction further, a between-subjects ANOVA was performed for each level of STIMULUS. The results, illustrated in figure 5.13, show that both with nouns [$F(2,37)= 13.37$; $p <0.001$] and with numbers [$F(2,37)= 3.58$; $p <0.05$], the difference between groups in the production of same list intrusion errors is significant. A Tukey's post-hoc test revealed that this difference is due to the F group performing significantly below the other two groups with nouns [$p<0.001$], but not with numbers. The other two groups do not significantly differ one from the other on any stimulus category.

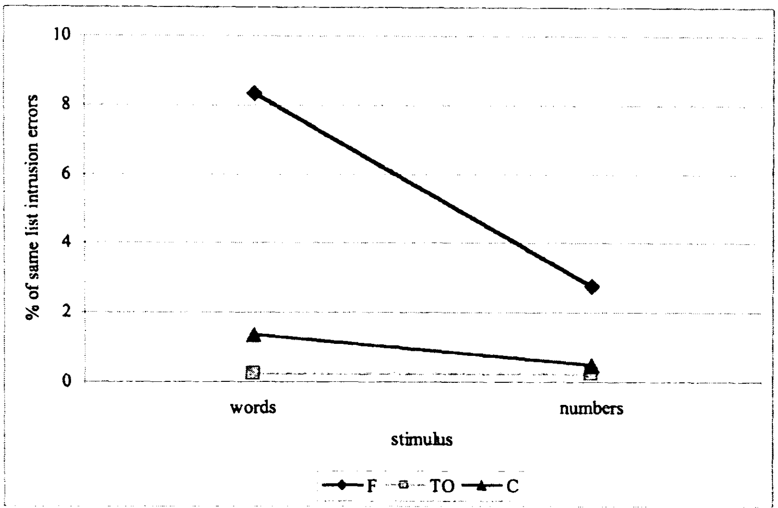

Figure 5. 13: Updating task - Same list intrusion errors - interaction STIMULUS X GROUP

The interaction INHIBITION X RECALL is significant [$F(2,71) = 3.72$, $p < 0.05$]. A Paired Samples t-test was conducted for each level of recall, comparing the performance at the different levels of inhibition. Figure 5.14 illustrates that the difference between low and high inhibition is only significant when the task requires to recall four items (R4 [$t(39)= -3.32$, $p<.02$]), but not at any other level of recall[181].

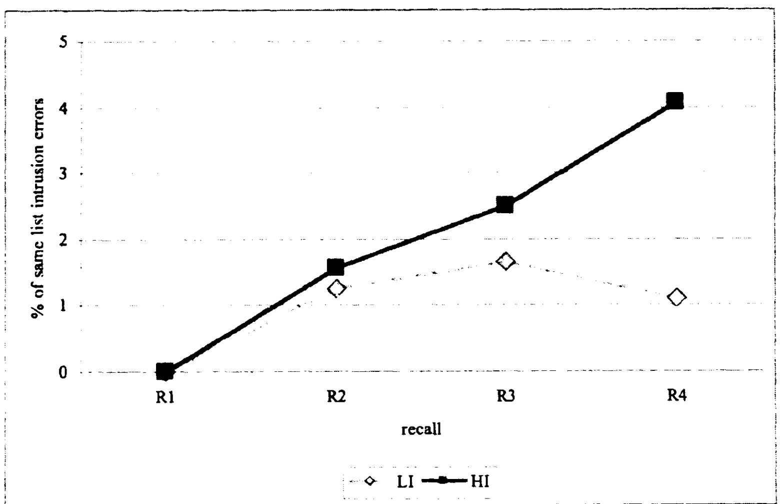

Figure 5. 14: Updating task - Same list intrusion errors - interaction INHIBITION X RECALL

[181] (R1) [n.s.: Could not compute the difference since all scores were equivalent], (R2) [$t(39)= -0.44$, $p>0.05$], (R3) [$t(43)= -1.16$, $p>0.05$].

Inhibition also interacts with stimulus: the interaction INHIBITION X STIMULUS is significant [$F(1,37) = 4.98$, $p<0.05$]. This was further investigated by conducting a Paired Sample t-test for each level of stimulus, comparing the percentage of intrusion errors from the same list at the different levels of inhibition. The results, illustrated in Figure 5.15, reveal that the difference between high and low inhibition is significant only with words [$t(39)= -3.20$, $p<0.01$] and not with numbers[182].

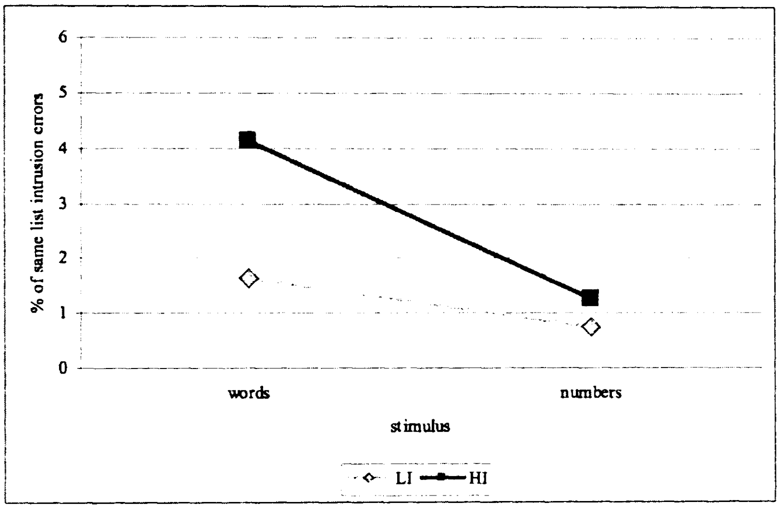

Figure 5. 15: Updating task - Same list intrusion errors - interaction INHIBITION X STIMULUS

The interaction RECALL X STIMULUS is significant [$F(2,80) = 4.10$, $p < 0.02$][183]. A Paired Samples t-test was conducted for each level of recall,

[182] [$t(39)= -1.00$, $p>0.05$].

[183] The other interactions (INHIBITION X GROUP [$F(2,37) = 1.47$, $p>0.05$], , INHIBITION X RECALL X GROUP [$F(4,71) = 0.61$, $p>0.05$], INHIBITION X STIMULUS X GROUP [$F(2,37)$ $= 0.83$, $p>0.05$]; RECALL X STIMULUS X GROUP [$F(4,80) = 2.30$, $p>0.05$], INHIBITION X RECALL X STIMULUS [$F(2,70) = 2.80$, $p>0.05$]; and INHIBITION X RECALL X STIMULUS X GROUP [$F(4,70) = 1.87$, $p>0.05$]) were not significant.

comparing the performance at the different levels of stimulus. This shows that the difference between the two levels of stimulus is not significant at any level[184].

PREVIOUS LIST INTRUSION ERRORS

A 3x2x4x2 mixed design ANOVA was conducted to assess differences between the three groups (F, TO, and C) across conditions in the production of intrusion errors of words from a list previously presented. The independent variables were the same as in the previous analysis. The dependent variable was the percentage of intrusions from a previous list (as a proportion of the total number of responses).

The analysis reveals a significant main effect of GROUP [$F(2,37) = 12.41$, $p<0.001$]. A Tukey's post-hoc analysis reveals that this is due to the F group performing significantly below both TO [$p<0.002$] and C [$p<0.001$] groups [185], as illustrated in Figure 5.16.

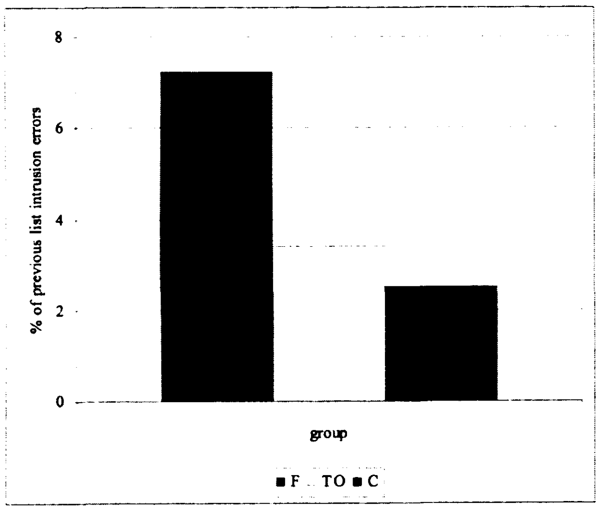

Figure 5. 16: Updating task - Previous list intrusion errors - main effect of GROUP

[184] when applying the Bonferroni correction , R1 [n.s.: Could not compute the difference since all scores were equivalent], R2 [$t(39)= -0.27$, p = n.s], R3 [$t(39)= 2.08$, $p>0.05$], R4 [$t(43)= 2.15$ $p>0.05$].

[185] The TO group instead did not differ from the control group [$p>0.05$].

The main effect of INHIBITION is significant [F(1,37) = 16.81, p<0.001], and it is explained by a higher percentage of intrusions from the previous list, when the load on control processes is high.

The main effect of RECALL is also significant [F(2,59) = 58.52, p<0.001]. A Polynomial contrast between the levels of recall shows that this variable is better accounted for by a quadratic[186] increase [F(1,37) = 42.40; p<.0.001], as illustrated in Figure 5.17. A little and similar difference can in fact be seen between one and two items to recall, and between two and three items to recall, but a larger difference can be observed between three and four items to recall.

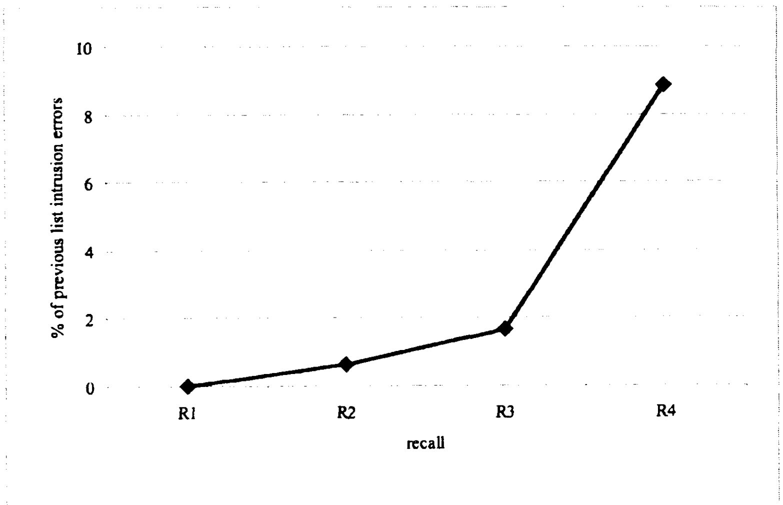

Figure 5. 17: Updating task - Previous list intrusion errors - main effect of RECALL

There is a significant main effect of STIMULUS [F(1,37) = 56.22, p<0.001]: a higher percentage of intrusions from the previous list errors is produced with numbers than with words.

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[186] A linear [F(1,37) = 79.52; p<.0.001] and cubic[F(1,37) = 11.45; p<0.005] increase were also found to be significant

The interaction RECALL X GROUP is significant [F(3,59) = 5.15, p<0.005]. A between-subjects ANOVA was performed for each level of recall, in order to further investigate the interaction. Figure 5.18 illustrates that when there is only one item to recall, there is no difference in the production of previous list intrusion errors between groups[187]. However, when the items to recall are more than one, the groups perform significantly differently (with R2 [F(2,37)= 6.06; p <0.01], R3 [F(2,37)= 17.36.13; p <0.01], and R4 [F(2,37)= 8.24; p <0.005]). A Tukey's post-hoc test shows that the F group performs significantly below the other two groups with R2 [p<0.02 compared to TO; p<0.01 compared to C], R3 [p<0.02 compared to TO; p<0.01 compared to C], and R4 [p<0.02 compared to TO; p<0.002 compared to C], whereas the other two groups do not significantly differ one from the other.

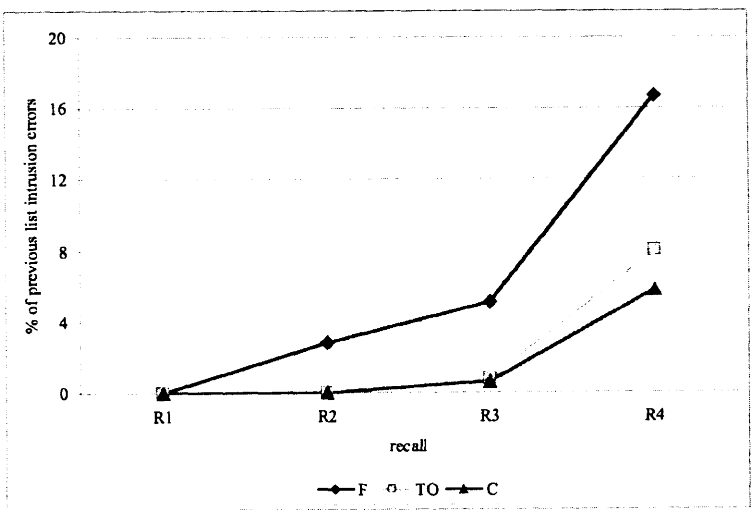

Figure 5. 18: Updating task - Previous list intrusion errors - interaction RECALL X GROUP

The factor GROUP also interacts with stimulus: the interaction STIMULUS X GROUP is significant [F(2,37) = 5.36, p<0.01]. To analyse it, a between-subjects ANOVA was performed for each level of stimulus. The results

[187] [n.s.: Could not compute the difference since all scores were equivalent]

show that the difference between groups in the production of previous list intrusion errors is significant when recalling numbers [$F(2,37)= 7.52$; $p < 0.005$], but not when recalling nouns[188]. A Tukey's post-hoc test shows that this difference is due to the F group performing significantly below both TO [$p<0.05$], and C [$p<0.002$] groups[189], when recalling numbers, as shown in Figure 5.19.

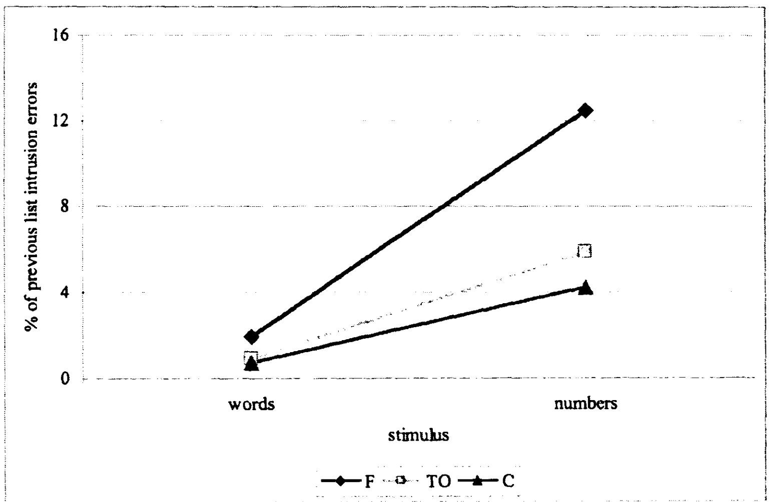

Figure 5. 19: Updating task - Previous list intrusion errors - interaction STIMULUS X GROUP

The interaction INHIBITION X RECALL is significant [$F(1,50) = 20.60$, $p < 0.001$]. A Paired Samples t-test was conducted for each level of recall, comparing the production of previous list intrusion errors at the different levels of inhibition. Figure 5.20 illustrates that the difference between low and high inhibition is only significant when the task requires the recall of four items (R4 [$t(39)= -5.13$, $p<0.005$], but it is not significant at the other levels of RECALL[190].

[188] [$F(2,37)= 13.37$; $p>0.05$]
[189] TO and C did not significantly differ one from the other.
[190] R1 [n.s.: Could not compute the difference since all scores were equivalent], R2 [$t(39)= 1.43$, $p>0.05$], R3 [$t(39)= -0.81$, $p>0.05$]

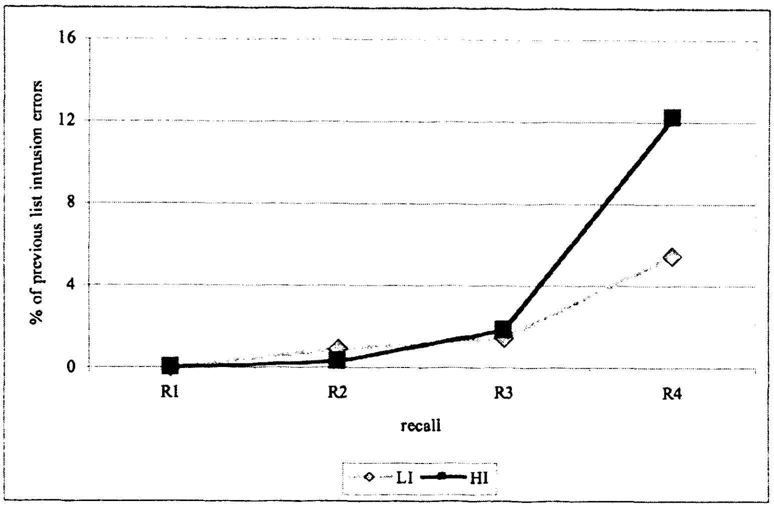

Figure 5. 20: Updating task - Previous list intrusion errors - interaction INHIBITION X RECALL

The interaction INHIBITION X RECALL X STIMULUS is also significant [$F(2,69) = 5.07$, $p < 0.02$][191]. This was further investigated by conducting separate Paired Samples t-tests for each level of stimulus. In each t-test the percentage of intrusion errors from a previous list in the condition of low inhibition was compared to the percentage of the same type of errors in the condition of high inhibition, at each level of recall. As illustrated in Figure 5.21, when the stimuli to be recalled are words, the difference in the percentage of previous list intrusions between low and high inhibition is not significant at any of the levels of recall[192]. When the task requires the recall of numbers, the difference in the percentage of previous list intrusions between low and high inhibition is only significant when the task requires the recall of four items (R4) [$t(39)= -4.69$, $p<.005$][193].

[191] The other interactions (INHIBITION X GROUP [$F(2,37) = 2.27$, $p>0.05$], INHIBITION X RECALL X GROUP [$F(3,50) = 0.56$, $p>0.05$], INHIBITION X STIMULUS X GROUP [$F(2,37) = 2.21$, $p>0.05$], and INHIBITION X RECALL X STIMULUS X GROUP [$F(4,69) = 1.20$, $p>0.05$]) were not significant.

[192] (R1 [n.s.: Could not compute the difference since all scores were equivalent], R2 [$t(39)= 1.00$, $p>0.05$], R3 [$t(39)= -1.35$, $p>0.05$, R4 [$t(39)= -2.08$, $p>0.05$])

[193] and not with R1 [n.s.: Could not compute the difference since all scores were equivalent], R2 [$t(39)= 0.57$, $p>0.05$], and R3 [$t(39)= -0.57$, $p>0.05$]

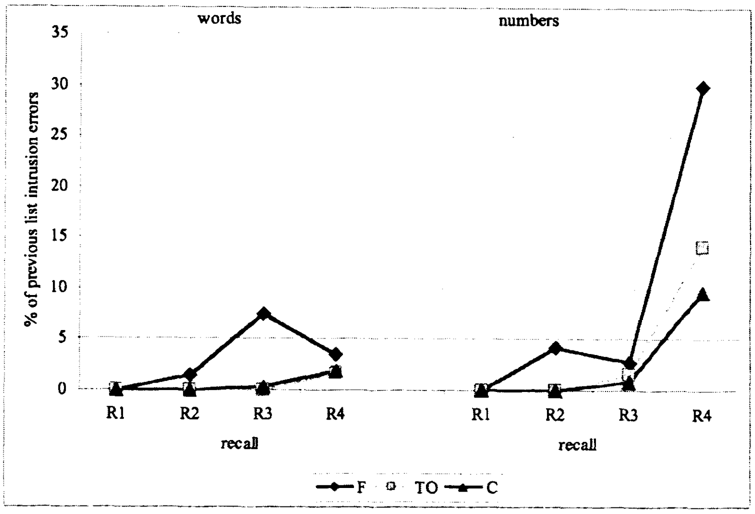

Figure 5. 21: Updating task - Previous list intrusion errors - interaction INHIBITION X RECALL X STIMULUS

Inhibition also interacts with stimulus: INHIBITION X STIMULUS is a significant interaction [$F(1,37) = 19.73$, $p<0.001$]. The interaction was further analyzed conducting a Paired Sample t-test at each level of stimulus, comparing the percentage of intrusion errors from a previous list at the different levels of inhibition. Figure 5.22 illustrates that the difference between low and high inhibition is significant only when recalling numbers [$t(39)= -5.10$, $p<0.002$] but not nouns[194].

[194] [$t(39)= -0.89$, $p>0.05$]

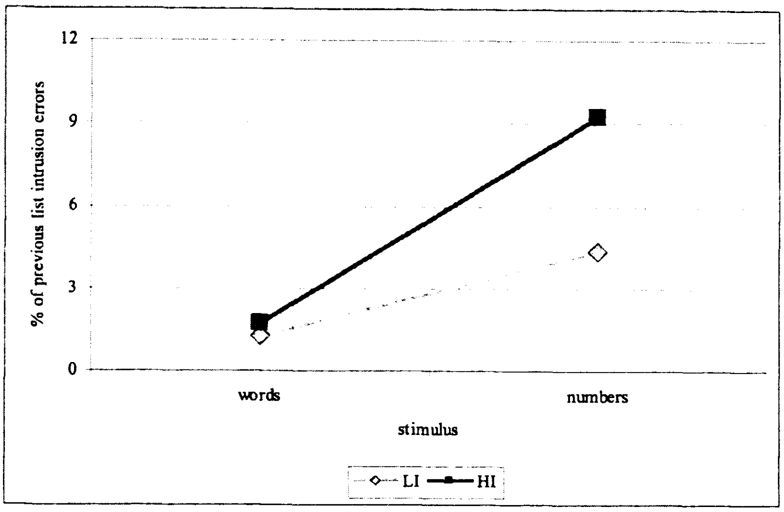

Figure 5. 22: Updating task - Previous list intrusion errors - interaction INHIBITION X STIMULUS

The interaction RECALL X STIMULUS is significant [$F(1,55) = 50.26$, $p < 0.001$]. A Paired Samples t-test was conducted for each level of recall, comparing the percentage of errors from a previous list at the different levels of stimulus. Figure 5.23 shows that the difference between nouns and numbers is significant only when having to recall four items (R4) [$t(39)= -6.22$; $p<0.005$][195].

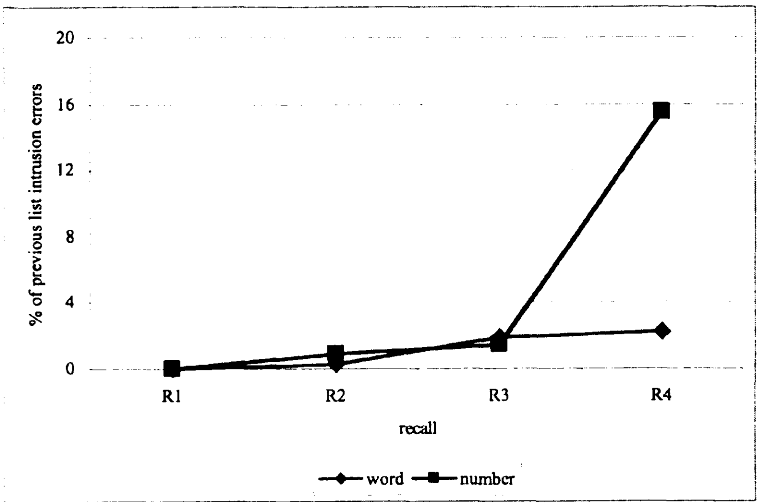

Figure 5. 23: Updating task - Previous list intrusion errors - interaction RECALL X STIMULUS

[195] The difference was not significant at any other level of RECALL (R1 [n.s.: Could not compute the difference since all scores were equivalent], R2 [$t(39)= -1.43$, $p>0.05$], R3 [$t(39)= 0.47$, $p>0.05$]).

Recall and stimulus also interact with group: the interaction RECALL X STIMULUS X GROUP is significant [$F(3,55) = 7.71$, $p<0.001$]. In order to further investigate the interaction, a separate ANOVA between the three groups of participants was performed for each level of stimulus, comparing the production of errors at each level of recall. The results, illustrated in Figure 5.24, show that, when the task requires the recall of nouns, the groups differ only with three items [$F(2,37) = 6.86$, $p<0.005$][196]. A Tukey's post-hoc test shows that this difference is attributable to the frontal group producing more intrusion errors from a previous list than both TO [$p<0.01$] and C [$p<0.005$]. When the task requires the recall of numbers, a significant difference is found in the production of errors when recalling two (R2) [$F(2,37) = 7.17$, $p<0.005$] and four (R4) [$F(2,37) = 8.97$, $p<0.002$] items[197]. Once again, a Tukey post-hoc test shows that the difference is due to the F group producing significantly more previous list intrusion errors than TO (with R2 $p<0.01$; with R4 $p<0.005$) and C (with R2 $p<0.02$; with R4 $p<0.001$) groups.

[196] and not with R1 [n.s.: Could not compute the difference since all scores were equivalent], R2 [$F(2,37) = 1.79$, $p>0.05$], or R4 [$F(2,37) = 0.63$, $p>0.05$]

[197] The difference was not significant with R1 [n.s.: Could not compute the difference since all scores were equivalent] and R3 [$F(2,37) = 1.15$, $p>0.05$].

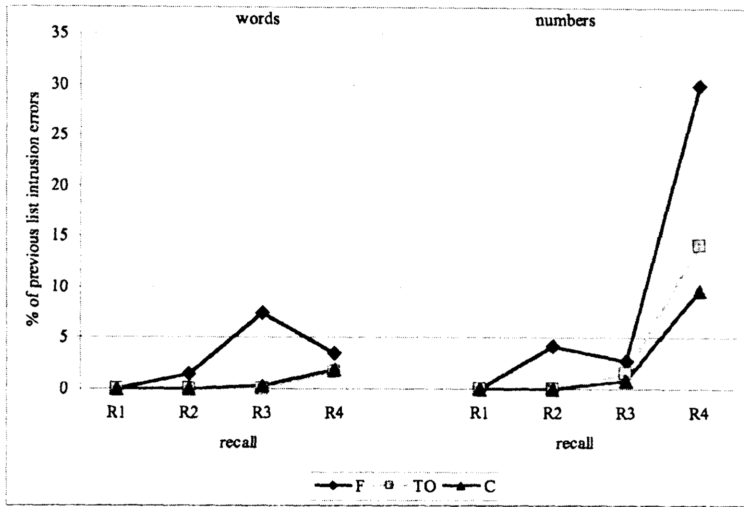

Figure 5. 24: Updating task - Previous list intrusion errors - interaction RECALL X STIMULUS X GROUP

INVENTION ERRORS

A 3x2x4x2 mixed design ANOVA was conducted to assess differences between the three groups (F, TO, and C) across conditions in the production of invention errors (i.e. the production of falsely recalled items: words or numbers that had not been previously presented). The independent variables were the same as in the previous analysis, and the dependent variable was the percentage of invention errors (as a proportion of the total number of responses).

The main effect of GROUP is not significant[198].

The analysis revealed that the main effect of INHIBITION is significant [$F(1,37) = 9.67$, $p<0.005$], and it is explained by a higher percentage of inventions when the load on control processes is high.

The main effect of RECALL is significant [$F(2,68) = 22.04$, $p<0.001$]. A Polynomial contrast between the levels of RECALL shows that this variable is

[198] [$F(2,37) = 1.25$, $p>0.05$]

better accounted for by a quadratic[199] increase ([F(1,37) = 33.12; p<0.001]. This means that a little and similar difference can be seen in the production of invention errors between one and two items to recall, and between two and three items to recall, but a larger difference can be observed between three and four items to recall, as illustrated in Figure 5.25.

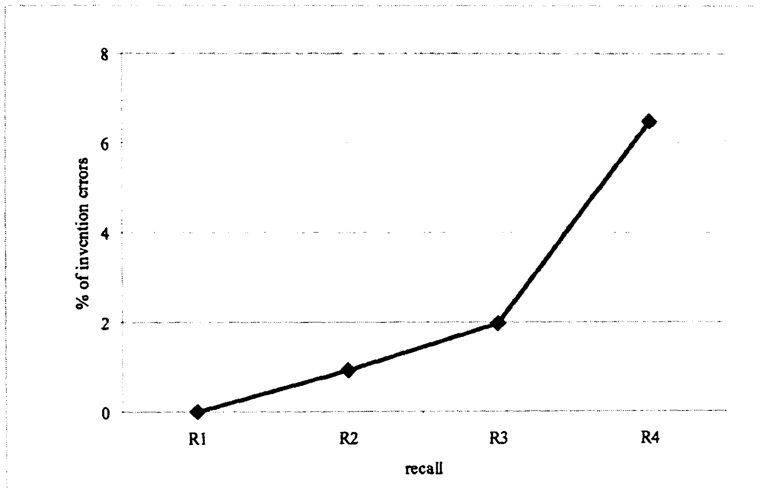

Figure 5. 25: Updating task - Invention errors - main effect of RECALL

STIMULUS is a significant main effect [F(1,37) = 24.85, p<0.001], due to a higher percentage of errors due to invention produced with numbers than with words.

The interaction STIMULUS X GROUP is significant [F(2,37) = 3.27, p<0.05]. A between-subjects ANOVA was performed for each level of stimulus, in order to further investigate the interaction. The results show that when recalling nouns[200] and when recalling numbers[201], the difference between groups in the production of invention errors is not significant. This interaction may be

[199] A linear [F(1,41) = 24.84; p<.0.001] and cubic[F(1,37) = 9.69; p<0.005] increase were also found to be significant.
[200] [F(2,37)= -0.42; p>0.05]
[201] [F(2,37)= 1.36; p>0.05]

due to a trend for more invention errors with numbers to be produced by the frontal group, as illustrated in Figure 5.26.

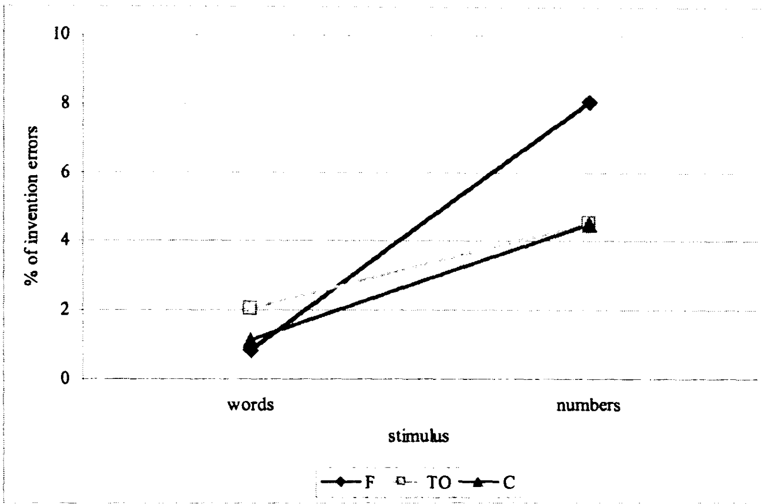

Figure 5. 26: Updating task - Invention errors - interaction STIMULUS X GROUP

The interaction INHIBITION X STIMULUS is significant [$F(1,37) = 5.37$, $p<0.05$]. This was further investigated by conducting a Paired Sample t-test for each level of stimulus, comparing the percentage of invention errors at the different levels of inhibition. Figure 5.27 shows that the difference between low and high inhibition is significant only when the task requires the recall of numbers [$t(39)= -3.11$, $p<0.01$] and not nouns[202].

[202] [$t(39)= -1.74$, $p>0.05$]

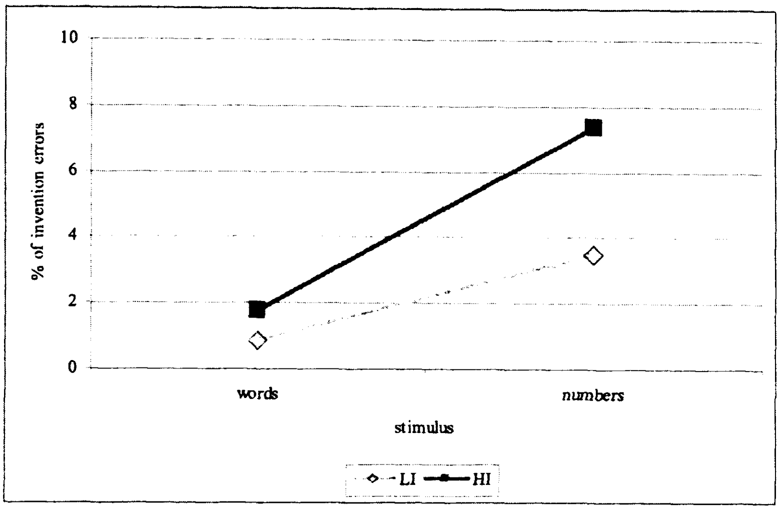

Figure 5. 27: Updating task - Invention errors - interaction INHIBITION X STIMULUS

Stimulus also interacts with recall: the interaction RECALL X STIMULUS is significant [$F(2,83) = 9.73$, $p < 0.001$][203]. In order to analyse the interaction, a Paired Samples t-test was conducted for each level of recall, comparing the percentage of errors from a previous list at the different levels of stimulus. Figure 5.28 illustrates that the difference between the two levels of stimulus is not significant when the task requires recalling only one item[204], but it is significant at all the other levels[205].

[203] The other interactions (INHIBITION X GROUP [$F(2,37) = 0.18$, $p>0.05$], RECALL X GROUP [$F(4,68) = 1.05$, $p>0.05$], INHIBITION X RECALL [$F(2,57) = 3.37$, $p>0.05$], INHIBITION X RECALL X GROUP [$F(3,57) = 0.96$, $p>0.05$], INHIBITION X STIMULUS X GROUP [$F(2,37) = 0.02$, $p>0.05$]; RECALL X STIMULUS X GROUP [$F(4,83) = 1.38$, $p>0.05$],), INHIBITION X RECALL X STIMULUS [$F(2,73) = 1.92$, $p>0.05$], and INHIBITION X RECALL X STIMULUS X GROUP [$F(4,73) = 0.97$, $p>0.05$] were not significant.

[204] (R1) [$t(43)= -1.67$, $p>0.05$]

[205] R2 [$t(43)= -4.64$, $p <0.005$], R3 [$t(43)= -3.96$, $p<0.005$] and R4 [$t(43)= -5.77$; $p<0.005$]

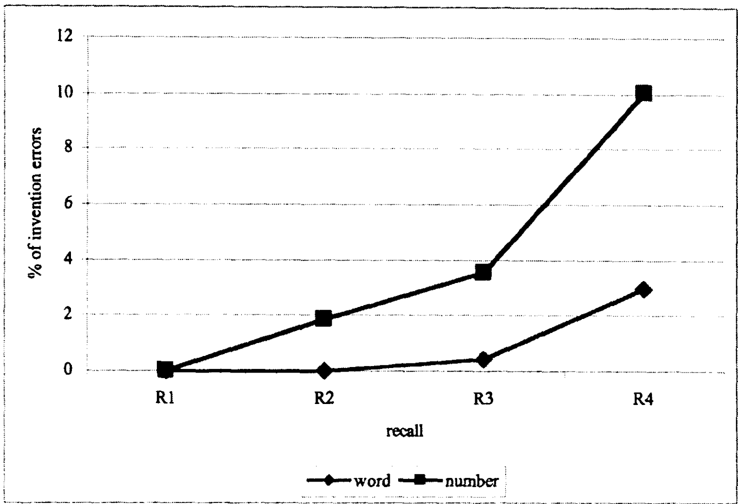

Figure 5. 28: Updating task - Invention errors - interaction RECALL X STIMULUS

OMISSION ERRORS

A 3x2x4x2 mixed design ANOVA was conducted to assess differences between the three groups (F, TO, and C) across conditions in the percentage of omissions (i.e., out of the total of items that the participant was asked to recall, the percentage of items not recalled at all). The independent variables were the same as in the previous analysis, and the dependent variable was the percentage of omissions (as a proportion of the total number of responses).

The analysis revealed a significant main effect of GROUP [$F(2,37) = 4.28$, $p<0.05$]. A Tukey's post-hoc analysis reveals that the differences between groups is due to the F group performing significantly below the C group [$p<0.02$], as illustrated in Figure 5.29. The two patient groups do not differ one from the other, nor do the TC group and the C group.

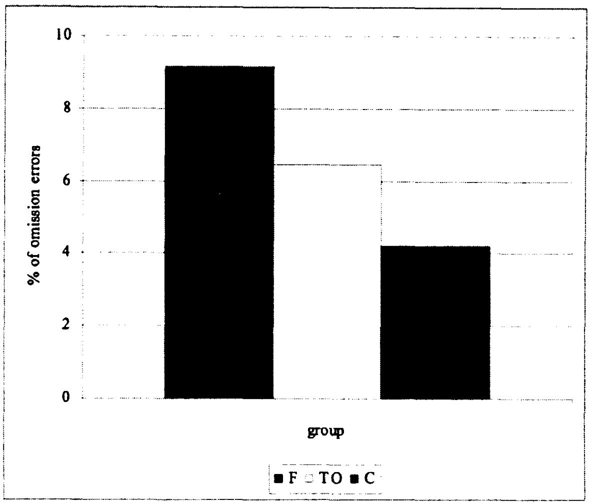

Figure 5. 29: Updating task - Omission errors - main effect of GROUP

The main effect of INHIBITION [$F(1,37) = 42.88$, $p<0.001$] is significant, due to a higher percentage of omissions when the load on control processes is high. RECALL is a significant main effect [$F(2,68) = 32.47$, $p<0.001$]. A Polynomial contrast between the levels of this factor shows that this variable is better accounted for by a quadratic[206] increase [$F(1,37) = 14.70$, $p<0.001$], This means that a little and similar difference can be seen in omission errors between one and two items to recall, and between two and three items to recall, but a larger difference can be observed between three and four items to recall, as illustrated in Figure 5.30.

[206] A linear [$F(1,37) = 46.19$; $p<.0.001$] and cubic [$F(1,37) = 15.19$; $p<.0.001$] increase were also found to be significant.

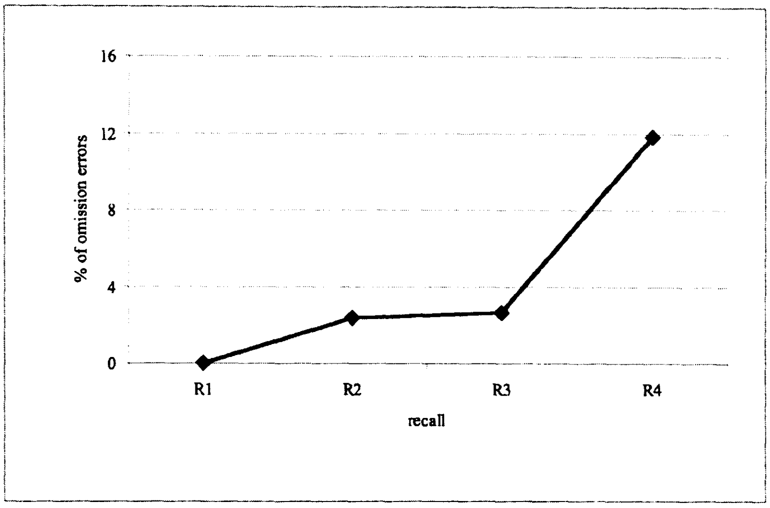

Figure 5. 30: Updating task - Omission errors - main effect of RECALL

The main effect of STIMULUS is significant [$F(1,37) = 6.87$, $p<0.02$], and it is explained by a higher percentage of omissions when the task requires the recall of nouns, compared to numbers.

The interaction INHIBITION X RECALL is significant [$F(1,51) = 25.94$, $p<0.001$]. A Paired Samples t-test was conducted for each level of recall, comparing the percentage of omission errors at the different levels of inhibition. Figure 5.31 illustrates that the difference between low and high inhibition is only significant when the task requires to recall three (R3) [$t(39)= -4.39$, $p<0.005$] or four items (R4) [$t(39)= -6.43$, $p<0.005$], and not at any of the other levels of recall[207].

207 R1 [n.s.: Could not compute the difference since all scores were equivalent], R2 [$t(39)= -1.00$, $p>0.05$]

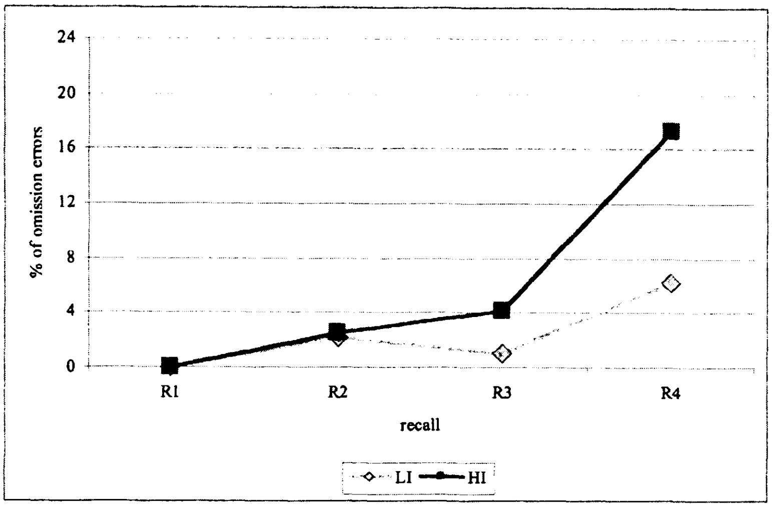

Figure 5. 31: Updating task - Omission errors - interaction INHIBITION X RECALL

The interaction RECALL X STIMULUS is significant [F(2,88) = 4.02, p<0.02]. A Paired Samples t-test was conducted comparing, for each level of recall, the percentage of omissions at the different levels of Stimulus. In all conditions of recall, the difference in the percentage of omissions was not significant[208].

Recall and stimulus also interact with inhibition: the interaction INHIBITION X RECALL X STIMULUS is significant [F(2,58) = 3.66, p<0.05][209]. This was further investigated by conducting two separate Paired Samples t-tests, one for each level of stimulus. In each t-test the percentage of omissions in the condition of low inhibition was compared to the percentage of the same type of error with high inhibition, at each level of recall. As illustrated in Figure 5.32, when the stimuli to be recalled are nouns, there is no significant

[208] with R1: [n.s.: Could not compute the difference since all scores were equivalent]; with R2: [t(39)= 1.68, p>0.05]; with R3: [t(39)= 0.17, p>0.05]; with R4: [t(39)= 2.24, p>0.05]

[209] The other interactions (INHIBITION X GROUP [F(2,37) = 1.29, p>0.05], RECALL X GROUP [F(4,68) = 1.50, p>0.05], STIMULUS X GROUP [F(2,37) = 1.07, p>0.05], INHIBITION X RECALL X GROUP [F(3,51) = 1.11, p>0.05.], INHIBITION X STIMULUS [F(1,37) = 4.09, p>0.05], INHIBITION X STIMULUS X GROUP [F(2,37) = 0.14, p>0.05], RECALL X STIMULUS X GROUP [F(5,88) = 2.33, p>0.05], and INHIBITION X RECALL X STIMULUS X GROUP [F(3,58) = 1.57, p>0.05] were not significant.

difference between low and high inhibition with one and two items to recall, but the difference is significant with three [t(39)= -3.37, p<0.05], four [t(39)= -3.63, p<0.005] nouns to be recalled[210]. With numbers to recall, the difference in the percentage of omissions between low and high inhibition is significant only when the task requires to recall four items (R4) [t(39)= -4.08, p<.005], but not at any other level of recall[211].

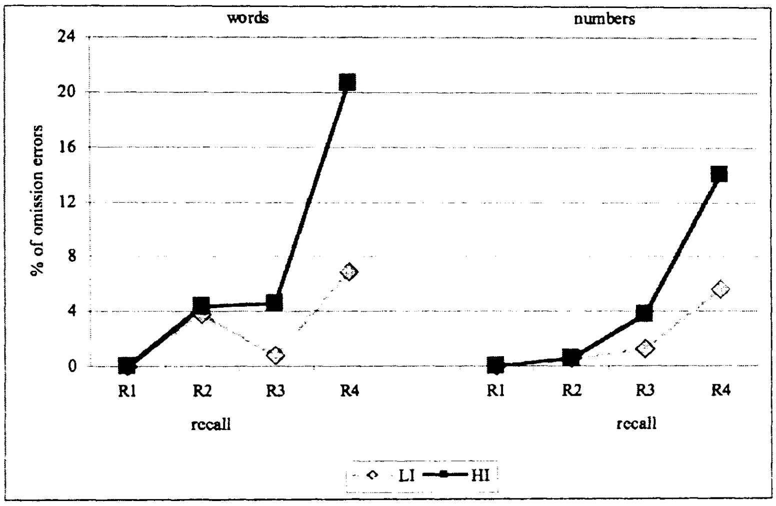

Figure 5. 32: Updating task - Omission errors - interaction INHIBITION X RECALL X STIMULUS

5.3.1.3. Summary of Updating Results

Table 5.3 illustrates a summary of the group effects on the Updating task. Recall performance is significantly poorer in the group with frontal brain lesions compared to the group with a posterior lesion and the group of healthy controls. This difference does not emerge when the updating task does not significantly tax maintenance processes (i.e. when having to recall only one item). The same pattern of results is observable when looking at the production of same list

[210] with R1 [n.s.: Could not compute the difference since all scores were equivalent], and R2 [n.s.: Could not compute the difference since all scores were equivalent].
[211] with R1 [n.s.: Could not compute the difference since all scores were equivalent], R2 [n.s.: Could not compute the difference since all scores were equivalent] and R3 [t(39)= -2.62, p>0.05].

intrusion errors. Moreover, the difference between groups can be observed when the task requires the recall of nouns, but not numbers. No effect of group is evident when looking at invention errors. The production of omission errors is significantly greater in the F group than in the C group. No difference is evident between the other groups.

Table 5. 3: Effects of group - summary of results

		RESULTS
RECALL	GROUP	F<C; F<TO; TO=C
	INHIBITION X GROUP	n.s.
	RECALL X GROUP	F<C; F<TO with R2; R3; R4
	STIMULUS X GROUP	n.s.
	INHIB X REC X GROUP	n.s.
	INHIB X STIM X GROUP	n.s.
	REC X STIM X GROUP	n.s.
	INHIB X REC X STIM X GROUP	significant
SAME LIST INTRUSIONS	GROUP	F<C; F<TO; TO=C
	INHIBITION X GROUP	n.s.
	RECALL X GROUP	F<C; F<TO with R2; R3; R4
	STIMULUS X GROUP	F<C; F<TO with N
	INHIB X REC X GROUP	n.s.
	INHIB X STIM X GROUP	n.s.
	REC X STIM X GROUP	n.s.
	INHIB X REC X STIM X GROUP	n.s.
PREVIOUS LIST INTRUSIONS	GROUP	F<C; F<TO; TO=C
	INHIBITION X GROUP	n.s.
	RECALL X GROUP	F<C; F<TO with R2; R3; R4
	STIMULUS X GROUP	F<C; F<TO with N
	INHIB X REC X GROUP	n.s.
	INHIB X STIM X GROUP	n.s.
	REC X STIM X GROUP	with W: F<C; F<TO with R3 with N: F<C; F<TO with R2; R4
	INHIB X REC X STIM X GROUP	n.s.
INVENTIONS	GROUP	n.s.
	INHIBITION X GROUP	n.s.
	RECALL X GROUP	n.s.
	STIMULUS X GROUP	n.s.
	INHIB X REC X GROUP	n.s.
	INHIB X STIM X GROUP	n.s.
	REC X STIM X GROUP	n.s.
	INHIB X REC X STIM X GROUP	n.s.

		RESULTS
OMISSIONS	GROUP	F<C; F=TO; TO=C
	INHIBITION X GROUP	n.s.
	RECALL X GROUP	n.s.
	STIMULUS X GROUP	n.s.
	INHIB X REC X GROUP	n.s.
	INHIB X STIM X GROUP	n.s.
	REC X STIM X GROUP	n.s.
	INHIB X REC X STIM X GROUP	n.s.

Key: F=Frontal participants; TO=Temporo-occipital participants; C=Controls; LI=Low Inhibition; HI=High Inhibition; R1;R2;R3;R4=1 item to recall; 2 items to recall etc.; W=Words (i.e. nouns); N=Numbers; > = better performance (i.e. more items recalled or fewer errors); < = worse performance (i.e. fewer items recalled or more errors); Decrease= decrease in performance (i.e. decrease in recall or increase in errors); n.s. = not significant.

5.3.2. Numerical Tasks

Performance of the F, TO, and C groups on the numerical tasks was compared. Due to the violation of normality assumption for the variables tested, a non-parametric analysis was performed. Two participants of the F group were not included in the analysis of the Transcoding from Arabic to verbal code, and one of these was also excluded from the analysis of Transcoding from verbal to Arabic code and of the Writing Numerals task. This was due to them performing at a level that rendered them outliers.

5.3.2.1. Writing Numerals

A Kruskal-Wallis Test was performed comparing performance on writing numerals in the three groups (F, TO, and C). As illustrated in Figure 5.33, there is a significant difference between groups in the writing Arabic numerals task [$\chi^2(2) = 7.95$; $p<0.02$]. No significant difference is evident between groups in writing verbal numerals[212], and writing words[213].

To further investigate the difference between groups in writing Arabic numerals, three Mann-Whitney Tests were conducted comparing the performance

[212] [$\chi^2(2) = 0.00$; $p>0.05$]
[213] [$\chi^2(2) = 0.00$; $p>0.05$]

of each of the groups with the other. Figure 5.33 shows that the group of frontal patients shows significantly poorer performance when writing Arabic numerals to dictation than the control group [Mann-Whitney U-Test = 60.00; Z = -2.28 p <0.05], whereas the other groups do not differ from each other[214].

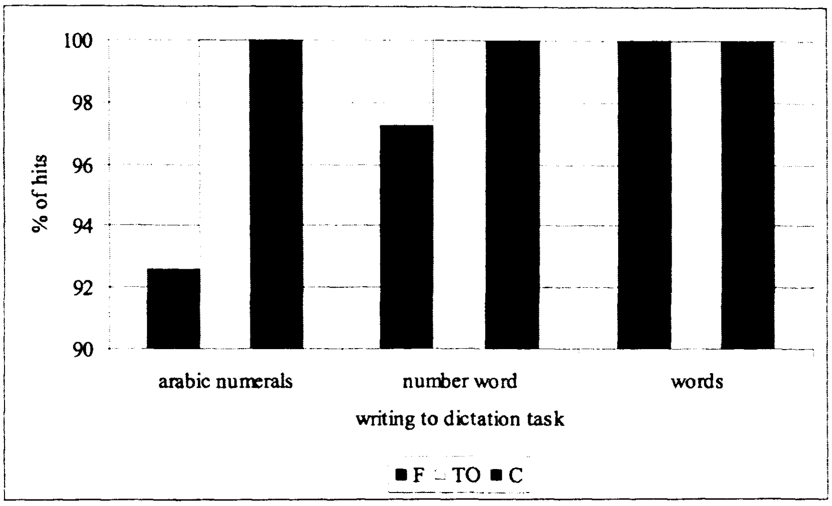

Figure 5. 33: Numerical tasks - Writing to dictation task - comparison between F, TO and C

5.3.2.2. *Reading Numerals and Transcoding Tasks*

A Kruskal-Wallis Test was performed comparing the performance of the three groups (F, TO, and C) on reading numerals and transcoding tasks. No difference was found in any of the reading tasks[215], or in the transcoding verbal to Arabic tasks[216]. A significant between-groups difference was found in the transcoding Arabic code to verbal code [$\chi^2(2) = 7.07$ $p<0.03$], as shown in Figure 5.34. In order to further investigate the difference between groups in the transcoding task from Arabic to verbal code, three Mann-Whitney tests were conducted comparing the performance of each of the groups with the others. Figure 5.34 illustrates that the difference between groups is due to the F group

[214] F vs. TO [Mann-Whitney U-Test = 33.00; Z = -1.70; p>0.05]; TO vs. C [Mann-Whitney U-Test = 110.00; Z=0.00; p>0.05].
[215] [$\chi^2(2) = 3.44$; p>0.05]
[216] [$\chi^2(2) = 0.00$; p>0.05]

performing below the C group [Mann-Whitney U-Test = 70.00; Z = -2.15 p <0.05]. The differences between the other groups are not statistically significant[217]. However, this difference was due to the poor performance of three participants of the frontal group. Therefore, this result cannot be generalised to patients with frontal lobe damage. It is of note that these participants were among the oldest in the group and their education was quite low.

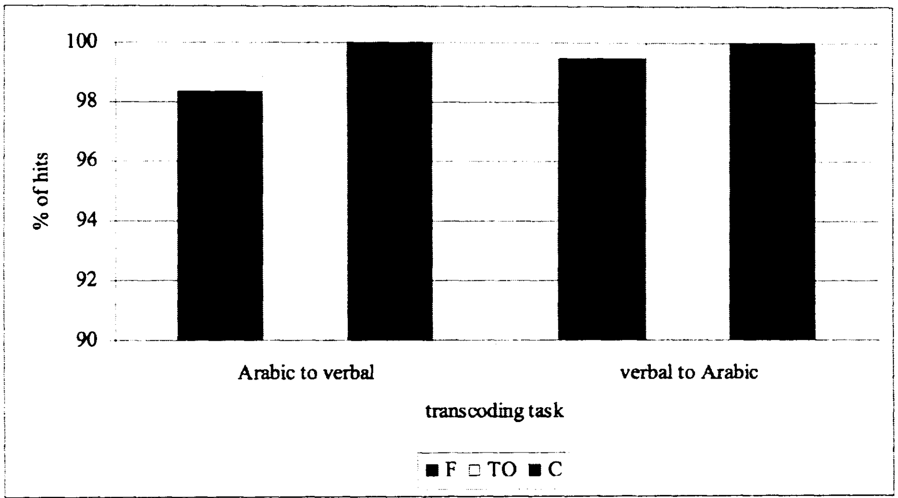

Figure 5. 34: Numerical tasks - Transcoding tasks - comparison between F, TO and C

5.3.3. Calculation Tasks

The three groups were also compared on the calculation tasks. Due to the violation of normality assumption for the variables tested, a non-parametric analysis was carried out to investigate arithmetical facts. The ANOVA was conducted to explore the Jackson & Warrington (1986) test and the Complex Mental Calculation task. One participant from the F group, two participants from the F group and two participants from the C group were excluded from the analysis of Arithmetical facts, Jackson & Warrington test, and Mental Calculation

[217] F vs. TO [Mann-Whitney U-Test = 38.5; Z = -1.60; p>0.05]; TO vs. C [Mann-Whitney U-Test = 110.00; Z=0.00; p>0.05].

Task respectively, due to their performance rendering them outliers. Bonferroni correction was used when multiple comparisons were performed on the data, and all the significance values reported include this correction where necessary.

5.3.3.1. *Arithmetical Facts*

A Kruskal-Wallis Test was performed comparing the performance on arithmetical facts in the three groups (F, TO, and C). As illustrated in Figure 5.35, there is a significant difference between groups in subtraction [$\chi^2(2) = 7.96$; $p<.02$] and multiplication, [$\chi^2(2) = 12.25$; $p<.005$], but not in addition[218].

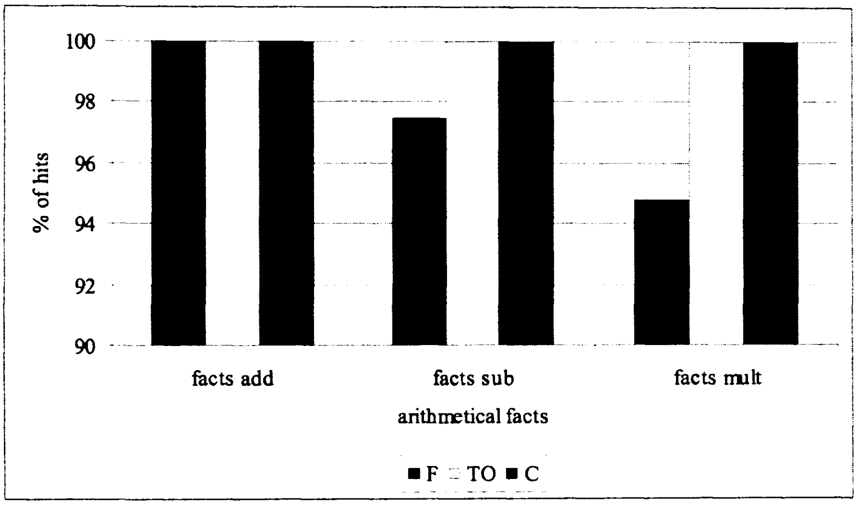

Figure 5. 35: Calculation tasks - Arithmetical facts - comparison between F, TO and C

In order to further investigate the difference between groups, three Mann-Whitney Tests were conducted, comparing the performance of each of the groups with the others, on subtraction and multiplication. Figure 5.36 shows that the differences found are due to the poorer performance of the frontal group compared to the group of patients with posterior lesions in multiplication [Mann-Whitney U-Test = 27.50; $Z = -2.15$ $p <0.05$], and compared to healthy controls in

[218] [$\chi^2(2) = 0.00$; $p>0.05$]

both subtraction [Mann-Whitney U-Test = 60.00; Z = -2.28 $p<0.05$] and multiplication [Mann-Whitney U-Test = 50.00; Z = -2.84 $p<0.005$][219].

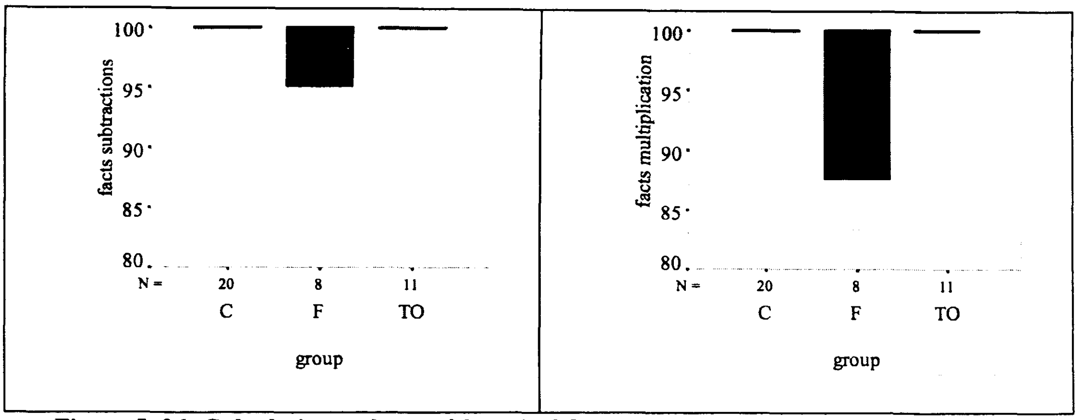

Figure 5. 36: Calculation tasks - Arithmetical facts - simple box plot of performance on subtraction and multiplication

5.3.3.2. Jackson & Warrington Test

A 3x2x3 mixed design ANOVA was conducted to investigate the differences in performance on mental calculation between the groups, in the Jackson & Warrington (1986) test. It further explored the effects due to the type of operation and difficulty (measured as the number of carryings/borrowings required to solve the problem). The between-subjects factor was GROUP with three levels (F, TO and C), and the within-subjects factors were: OPERATION with two levels (ADD and SUB), and CAR/BOR with three levels (0 c/b; 1 c/b; 2 c/b). The dependent variable was the percentage of correct responses (hits).

Table 5.4 summarises the results of the Jackson and Warrington test.

[219] Subtraction: F vs. TO [Mann-Whitney U-Test = 33.00; Z = -1.70; $p>0.05$]; TO vs. C [Mann-Whitney U-Test = 110.00; Z=0.00; $p>0.05$]. Multiplication: TO vs. C [Mann-Whitney U-Test = 110.00; Z=0.00; $p>0.05$].

Table 5. 4: Jackson and Warrington Task - results

	RESULTS
GROUP	F<C; F<TO; TO=C
OPERATION	ADD>SUB
CAR/BOR	Linear decrease
OPERATION X GROUP	n.s.
CAR/BOR X GROUP	F<C with 0c/b; 1c/b; 2c/b F<TO with 0c/b; 1c/b
OPERATION X CAR/BOR	ADD>SUB with 2c/b
OPERATION X CAR/BOR X GROUP	n.s.

Key: F=Frontal participants; TO=Temporo-occipital participants; C=Controls; 0c/b= 0 carryings/borrowings; 1c/b= 1 carrying/borrowing; 2c/b=2 carryings/borrowings; > = better performance; < = worse performance; Decrease= decrease in performance; n.s. = not significant

The analysis reveals a significant main effect of GROUP [F(1,35) = 13.51; p<0.001]. A post-hoc test (Tukey's) was used to explore which groups showed significantly different performance. The results, as illustrated in Figure 5.37, show that the F group has significantly poorer performance in this test, compared to both TO [p<0.01] and C [p<0.001] groups. The TO and C groups do not differ in terms of performance.

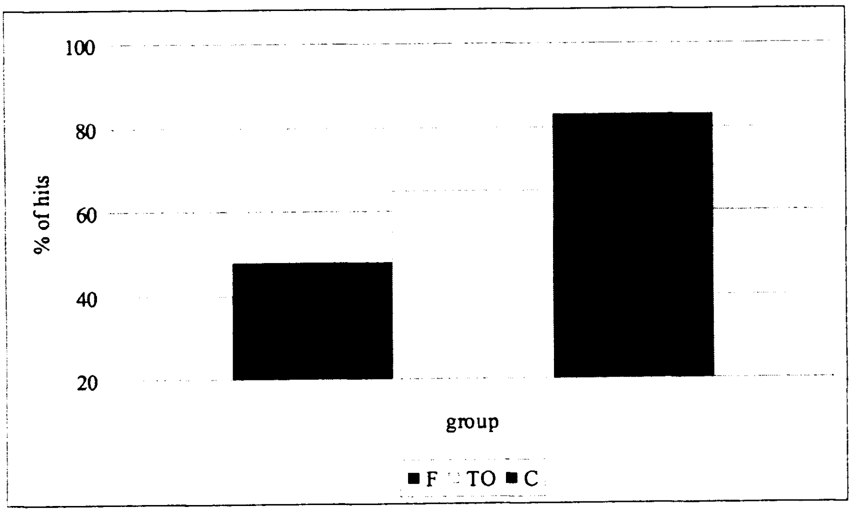

Figure 5. 37: Calculation tasks - Jackson & Warrington test - main effect of GROUP

The main effect of OPERATION is significant [F(1,35) = 21.98; p<0.001], and is explained by performance with addition being better than with subtraction.

The main effect of CAR/BOR is significant [$F(2,53)= 83.88$; $p<0.001$]. A polynomial contrast confirmed that this factor shows a significantly linear decrease [$F(1,35) = 107.66$; $p<.0.001$]. This indicates that performance on the task decreases proportionally at the increase of difficulty, as illustrated in Figure 5.38. No other significant trends were observed.

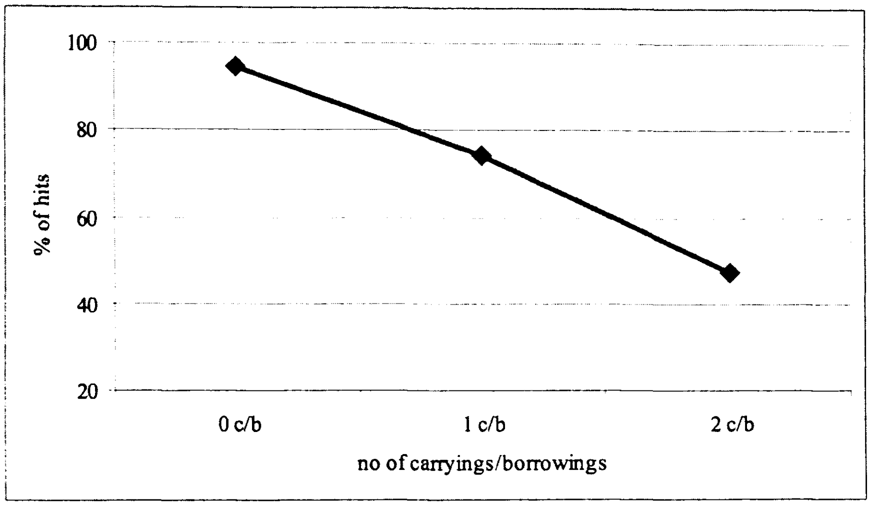

Figure 5. 38: Calculation tasks - Jackson & Warrington test - main effect of CAR/BOR

The interaction CAR/BOR X GROUP is significant [$F(3,53) = 3.00$; $p<0.05$]. The interaction was further explored by conducting a between-subjects ANOVA with GROUP as a between-subjects independent variable, and the performances at each of the three levels of CAR/BOR as dependent variables. Figure 5.39 illustrates that there is a significant difference between groups at all levels of CAR/BOR (with 0 c/b [$F(2,35) = 25.02$; $p<0.001$]; with 1 c/b [$F(2,35) = 11.81$]; $p<0.001$] and with 2 c/b [$F(2,35) = 7.11$; $p<0.005$]). A post-hoc (Tukey's) test reveals that this difference is due to the F group performing significantly below the TO group, but only when the operation requires the use of up to one carrying/borrowing operation (with 0 c/b [$p<0.001$] and 1 c/b [$p<0.02$]). Moreover, the F group performs below the C group at all levels of CAR/BOR (with 0 c/b [$p<0.001$], 1 c/b [$p<0.001$], and 2 c/b [$p<0.005$]). The TO group does not differ from the C group at any level.

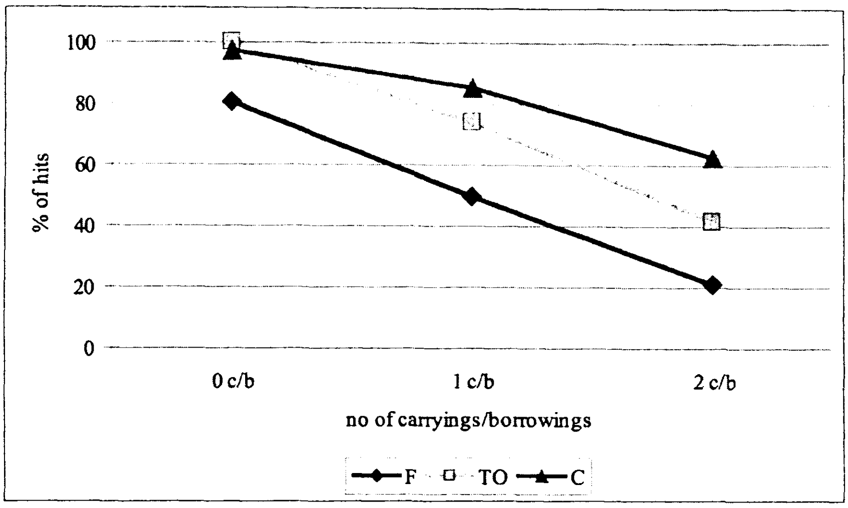

Figure 5. 39: Calculation tasks - Jackson & Warrington test - interaction CAR/BOR X GROUP

The number of carrying/borrowings required to solve the problem also interacts with operation: the interaction OPERATION X CAR/BOR is significant [$F(1,52) = 7.25$; $p<0.005$][220]. This was further investigated by conducting a Paired Samples t-test at each level of CAR/BOR, comparing the two levels of OPERATION. Figure 5.40 shows that the difference in performance between addition and subtraction is only significant when the operation is most difficult (i.e. with 2 carryings/borrowings in the operation) [$t(37) = 5.45$; $p<0.005$][221].

[220] The other interactions were not found to be significant (OPERATION X GROUP [$F(2,35) = 0.45$; $p>0.05$]; OPERATION X CAR/BOR X GROUP [$F(3,52) = 2.05$; $p>0.05$]).
[221] No difference was found with 0 c/b [$t(37) = -0.18$; $p>0.05$] and 1 c/b [$t(37) = -0.08$; $p>0.05$].

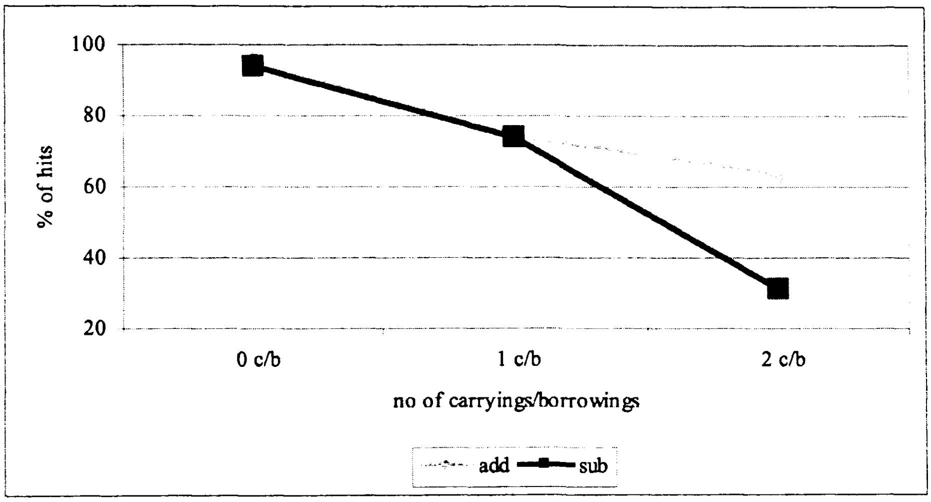

Figure 5. 40: Calculation tasks - Jackson & Warrington test - interaction OPERATION X CAR/BOR

5.3.3.3. Complex Mental Calculation

A 3x2x3 mixed design ANOVA was conducted to investigate the differences in performance on complex mental calculation (with visual presentation) between the three groups, and to explore the effects of type of operation and difficulty (measured as the number of carryings/borrowings required for the solution of the problem). The independent and dependent variables were the same as in the analysis of the Jackson and Warrington (1986) test.

Table 5.5 summarises the results in the complex mental calculation tasks.

Table 5. 5: Complex Mental Calculation Task - results

	RESULTS
GROUP	F<C; F<TO; TO=C
OPERATION	ADD>SUB
CAR/BOR	Linear decrease
OPERATION X GROUP	n.s.
CAR/BOR X GROUP	F<C with 0c/b; 1c/b; 2c/b F<TO with 0c/b; 1c/b
OPERATION X CAR/BOR	ADD>SUB with 1c/b; 2c/b
OPERATION X CAR/BOR X GROUP	In F ADD=SUB In TO ADD>SUB with 1c/b; 2c/b In C ADD>SUB with 2c/b

Key: F=Frontal participants; TO=Temporo-occipital participants; C=Controls; 0c/b= 0 carryings/borrowings; 1c/b= 1 carrying/borrowing; 2c/b=2 carryings/borrowings; > = better performance; < = worse performance; Decrease= decrease in performance; n.s. = not significant

The main effect of GROUP is significant [F(2,35) = 24.41; p<0.001]. A post-hoc test (Tukey's) was carried out to explore which groups had a significantly different performance. Figure 5.41 shows that group F's performance is significantly below both TO [p<0.002] and C [p<0.001], whereas TO and C do not differ in terms of performance.

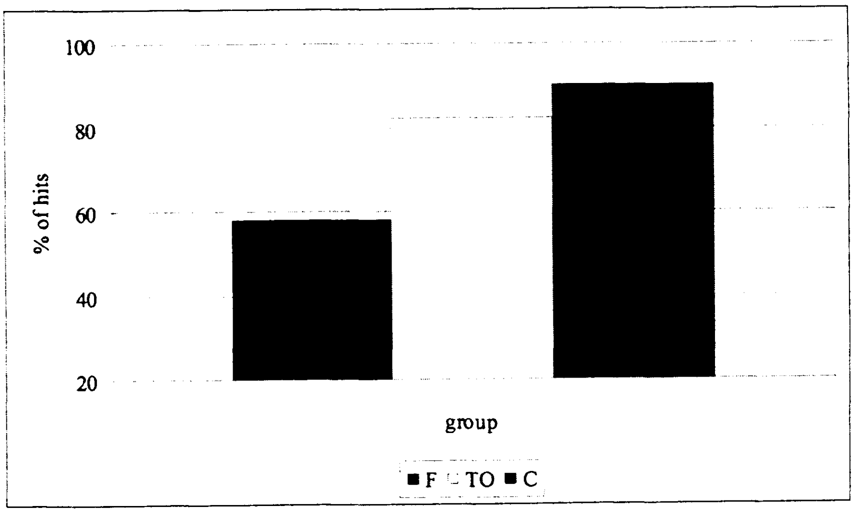

Figure 5. 41: Calculation tasks - Complex mental calculation - main effect of GROUP

The main effect of OPERATION is significant [F(1,35) = 25.52; p<0.001], due to performance on addition being better than in subtraction. The analysis also reveal a significant main effect of CAR/BOR [F(1,47)= 188.66; p<0.001]. A polynomial contrast confirmed that this factor is better accounted for by a linear[222] decrease [F(1,35) = 238.62; p<.0.001], meaning that performance on the task decreases proportionally at the increase of difficulty, as illustrated in Figure 5.42.

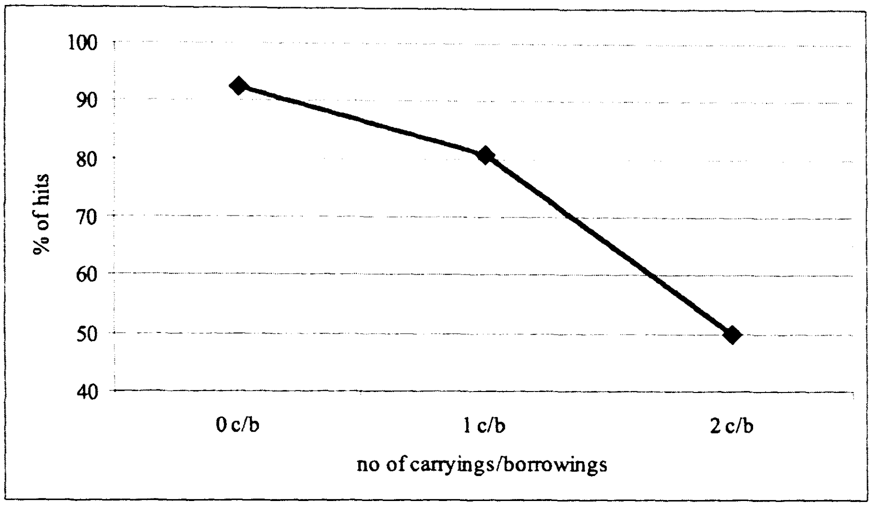

Figure 5. 42: Calculation tasks - Complex mental calculation - main effect of CAR/BOR

The interaction CAR/BOR X GROUP is significant [F(3,47) = 11.03; p<0.001], and it was further investigated by conducting a between-subjects ANOVA with GROUP as a between-subjects independent variable, and the percentage of correct responses at each of the three levels of CAR/BOR as a dependent variable. Figure 5.43 shows that there is a significant difference between groups at all the levels of CAR/BOR (with 0 c/b [F(2,35) = 19.03; p<0.001]; with 1 c/b [F(2,35) = 24.39]; p<0.001] and with 2 c/b [F(2,35) = 19.27; p<0.001]). A post-hoc Tukey's test reveals that this difference is due to the F group performing significantly worse than the TO group when the task requires the use of up to one carrying/borrowing operation (with 0 c/b [p<0.001] and 1 c/b [p<0.001]). Moreover, the F group performs worse than the C group at all levels

[222] A quadratic decrease was also found to be significant [F(1,35) = 38.81; p<0.001

of CAR/BOR (with 0 c/b [p<0.001], 1 c/b [p<0.001], and 2 c/b [p<0.001]). The TO group is worse than the C group only with 2 c/b [p<0.001].

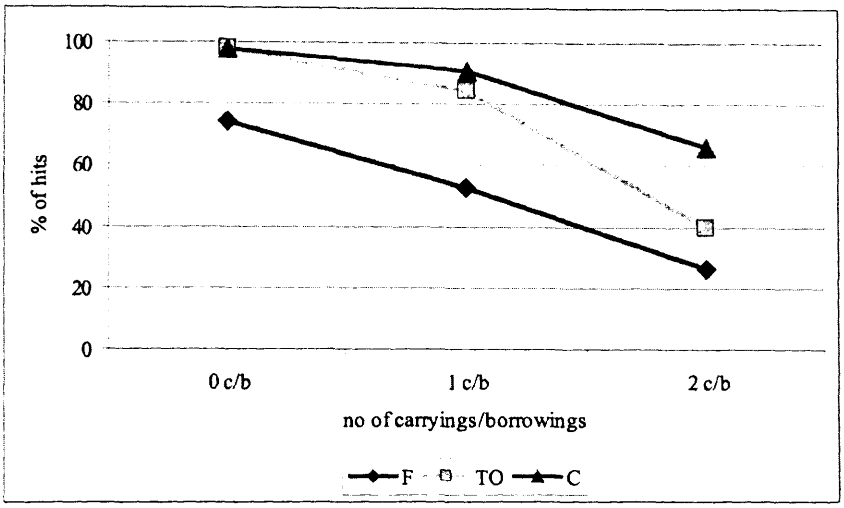

Figure 5. 43: Calculation tasks - Complex mental calculation - interaction CAR/BOR X GROUP

The interaction OPERATION X CAR/BOR is significant [F(2,54) = 6.14; p<0.01]. This was explored by conducting a Paired Samples t-test at each level of CAR/BOR, comparing the two levels of OPERATION. The results, illustrated in figure 5.44, show that the difference in performance between addition and subtraction is only significant when the operation requires carryings/borrowings for its solution (i.e. one [t(37) = 3.28; p<0.01] or two [t(37) = 4.59; p<0.005])[223].

[223] No significant difference was found with 0 c/b [t(37) = -0.18; p>0.05].

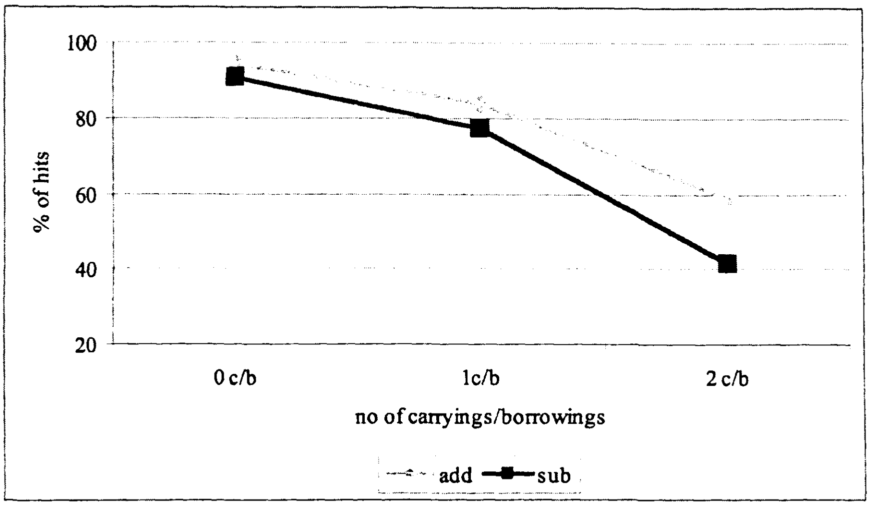

Figure 5. 44: Calculation tasks - Complex mental calculation - interaction OPERATION X CAR/BOR

The type of operation and the number of carryings/borrowings required to solve the problem also interact with group: the interaction OPERATION X CAR/BOR X GROUP is significant [$F(3,54) = 3.08$; $p<0.05$][224]. This interaction was further investigated by conducting the same analysis in the three groups separately. Figure 5.45 shows that the three groups performed differently from one another. Within group F, there is no difference in performance with addition and subtraction[225]. Within group TO, performance on addition problems was better than performance on subtraction problems when they required one [$t(10) = 3.29$; $p<0.05$] or two [$t(10) = 3.61$; $p <0.02$] carryings/borrowings for their solution[226]. Within group C, performance on addition problems was better than performance on subtraction problems only when they required the use of two carrying/borrowings [$t(17) = 4.64$; $p<0.005$] for their solution[227].

[224] The other interaction (OPERATION X GROUP [$F(2,35) = 0.41$; $p>0.05$]) was not significant.
[225] with 0 c/b [$t(8) = -1.91$; $p>0.05$], with 1 c/b [$t(8) = 1.62$; $p>0.05$], with 2 c/b [$t(8) = 0.72$; $p>0.05$].
[226] with 0 c/b [$t(10) = -0.24$; $p>0.05$]
[227] with 0 c/b [$t(17) = -0.80$; $p>0.05$],with 1 c/b [$t(17) = 0.94$; $p>0.05$].

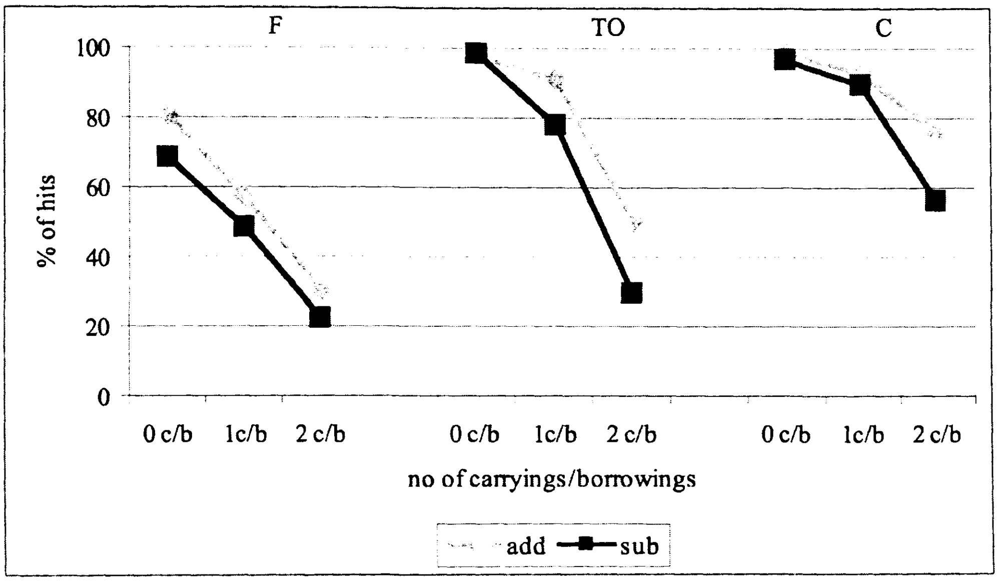

Figure 5. 45: Calculation tasks - Complex mental calculation - interaction OPERATION X CAR/BOR X GROUP

5.3.3.4. Complex Mental Calculation: Verbal versus Visual Presentation

A 3x2x2 mixed design ANOVA was conducted to explore the differences in performance between the two groups comparing verbal to written presentation and also addition to subtraction. The between-subjects factor was GROUP with three levels (F, TO and C), and the within-subjects factors were: OPERATION with two levels (ADD and SUB), and PRESENTATION with two levels (VERBAL and VISUAL). The dependent variable was the percentage of correct responses on the items in common between the Jackson & Warrington (1986) test and the Complex Mental Calculation Task (i.e. all the items of the Jackson & Warrington (1986) test and the 28 items in the Complex Mental Calculation Task containing the same operations).

The main effect of GROUP is significant [$F(2,35) = 20.17$; $p<0.001$]. A Tukey post-hoc test was carried out to explore which groups performed differently. Figure 5.46 illustrates that group F has a significantly poorer performance than both TO [$p<0.01$] and C [$p<0.001$] groups. Moreover, group TO performs significantly worse than group C [$p<0.02$].

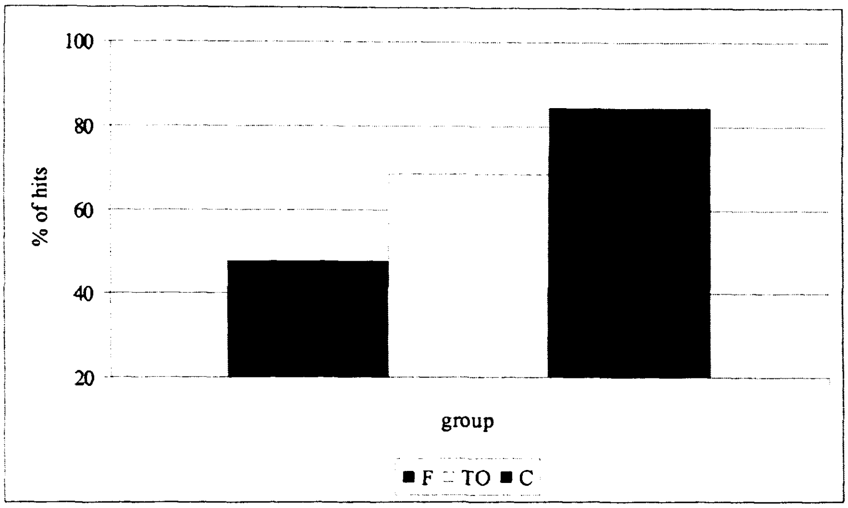

Figure 5. 46: Calculation tasks - Complex mental calculation - verbal vs. visual - main effect of GROUP

The main effects of OPERATION[228] and PRESENTATION[229] are not significant. The interaction OPERATION X PRESENTATION is significant [$F(1,35) = 4.65$; $p<0.05$][230]. To further analyse this interaction, a Paired Samples t-test was conducted, comparing performance with visual and verbal presentation at each level of OPERATION. Figure 5.47 clearly illustrates that the difference in performance between visual and verbal presentation is significant with subtraction [$t(37)= -2.46$, $p<0.05$], but not addition problems[231].

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[228] [$F(1,35) = 1.59$; $p>0.05$]
[229] [$F(1,35)= 2.98$; $p>0.05$]
[230] The other interactions (OPERATION X GROUP [$F(2,35) = 0.74$; $p>0.05$]; PRESENTATION X GROUP [$F(2,35) = 0.52$; $p>0.05$]); and OPERATION X PRESENTATION X GROUP [$F(2,35) = 1.05$; $p>0.05$] were not significant.
[231] with addition problems: [$t(37)= -0.49$, $p>0.05$]

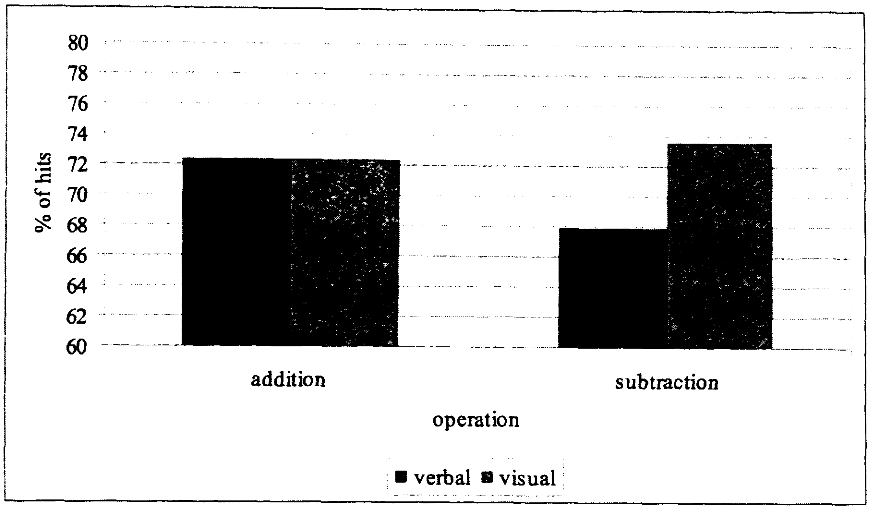

Figure 5. 47: Calculation tasks - Complex mental calculation - verbal vs. visual - interaction OPERATION X PRESENTATION

5.3.4. The Relationship between Working Memory and Calculation

In order to understand the relationship between WM and complex mental calculation, linear regression analyses were conducted for the three groups of participants, to investigate possible associations between measures of WM and performance on complex mental calculation tasks. A linear regression analysis was conducted with performance on the Jackson & Warrington (1986) test as a dependent variable and the digit span test backwards performance as the independent variable. A further regression analysis with Complex Mental Calculation task as a dependent variable and digit span test backwards as the independent variable was also performed.

The results show that performance on the digit span backwards explains 65.7% of the variance in the Jackson & Warrington (1986) test in the F group [$R^2 = 0.657$; $p<0.01$], 54.2% of the variance in the TO group [$R^2 = 0.542$; $p<0.02$], and the 61.9% of the variance in the C group [$R^2 = 0.619$; $p<0.001$]. It also explains 46.1% of the variance in the Complex Mental Calculation task in the C group [R^2 = 0.461; $p < 0.002$], but it does not significantly explain the variance this task in the F group[232], and in the TO group[233].

A further two regression analysis included WM total recall as an independent variable and either performance on the Jackson & Warrington (1986) test or the Complex Mental Calculation task, as dependent variables. WM total recall explains 61.2% of the variance in the Jackson & Warrington (1986) test in the F group [R^2 =0.612; $p<0.02$], and 65.0% of the variance in the TO group [R^2 =0.650; $p<0.005$], but it does not significantly explain for the variance in this test in the C group[234]. WM total recall also explains 61.7% of the variance in the Complex Mental Calculation task in the F group [R^2 =0.617; $p<0.02$], and 55.3% of the variance in the TO group [R^2 =0.553; $p<0.01$], but it does not significantly explain for the variance in this task in the C group[235].

A further two regression analyses studied WM total intrusions from the same list as an independent variable and either performance on the Jackson & Warrington (1986) test or the Complex Mental Calculation task as dependent variables. They show that WM total intrusions do not significantly explain any of the variance in the Jackson & Warrington (1986) test for any of the groups[236]. It also does not explain the variance in the Complex Mental Calculation Task in any of the groups[237].

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[232] [R^2 = 0.257; $p>0.05$]
[233] [R^2 = 0.243; $p>0.05$]
[234] [R^2 =0.180; $p>0.05$]
[235] [R^2 =0.123; $p>0.05$]
[236] F group [R^2 = 0.223; $p>0.05$], TO group [R^2 = 0.194; $p>0.05$], C group [R^2 = 0.131; $p>0.05$]
[237] F group [R^2 = 0.435; $p>0.05$], TO group [R^2 = 0.044; $p>0.05$], C group [R^2 = 0.008; $p>0.05$]

5.4. Discussion

5.4.1. The effects of frontal lobe damage on WM

The first aim of this preliminary study was to investigate the processes of interest in the previous chapters in people with a frontal lobe lesion, to assess whether specific components of WM were selectively affected in this population. In particular it was expected that people with a frontal lobe lesion would have difficulties in executing control processes (Luria, 1966; 1969; Shallice, 1982). It is important to note that, given the limited size of the groups studied and the different age and education of the two clinical groups, this is a preliminary study that should serve as an indication of whether further investigate similar groups in future research on WM.

On the span tests, similar overall effects of stimulus and length were seen compared with the other populations studied: performance on the digit span is better than performance on the span tests involving bi-syllabic words (i.e. nouns and proper names). No length effect was found for nouns and proper names. As predicted, differences between groups were only evident in a task involving greater executive control (i.e. the digit span backwards): lower performance was found in the group with frontal lobe damage compared to the group of healthy adults, but not compared to the other patients group. Interestingly no significant differences were found between the group with posterior lesions and either of the other two groups. This can be explained by hypothesizing a slight decrease in executive control over a STM task (i.e. a task that requires one to manipulate the information to be recalled, and is likely to involve CE) due to brain damage, but that this decrease only becomes significant when the lesion involves the frontal region of the brain. No other differences between the groups were expected in the span tests, considered to be measuring the PL, consistent with the idea that only control processes are affected by frontal lobe lesions.

As in the previous studies described in this thesis, WM was investigated by investigating distinct aspects of the CE: its maintenance and control processes. The predictions about the effects of group and the results found are illustrated in Table 5.7. The hypothesis was that planning, regulating and control processes are required for good performance on the updating task and in particular in the inhibition of irrelevant information. It was also hypothesised that people with a frontal lobe lesion would have greater difficulty in these processes (Luria, 1966; 1969; Shallice, 1982). Therefore, poorer performance on the inhibition of irrelevant information (i.e. control processes) was expected and observed in a group with frontal lobe lesions compared to a group of healthy controls and a group with more posterior damage (temporo-occipital). Recall performance, interpreted as a measure of the ability to update relevant information, was found to be impaired in the frontal group compared to both the posterior group and the healthy control group. It would therefore appear that the overall processing capacity of the CE is impaired by a frontal lesion. This is not coherent with the prediction based on Baddeley (1986) that in dysexecutive syndrome control processes are deficient but do not lead to a decrease in the overall processing capacity. It is of note, however, that in the present study the participants with frontal lobe damage do not show signs of dysexecutive syndrome, as measured by standard tests.

Table 5. 6: Updating task - Effects of Group- predictions and results

		PREDICTIONS	RESULTS
RECALL	GROUP	n.s.	F<C; F<TO; TO=C
	INHIBITION X GROUP	More affected by load on control in F	n.s.
	RECALL X GROUP	-	F<C; F<TO with R2; R3; R4
	STIMULUS X GROUP	-	n.s.
	INHIB X REC X GROUP	In F LI>HI also with fewer items to recall	n.s.
	INHIB X STIM X GROUP	-	n.s.
	REC X STIM X GROUP	-	n.s.
	INHIB X REC X STIM X GROUP	-	significant
SAME LIST INTRUSIONS	GROUP	F<C; F<TO; TO=C	F<C; F<TO; TO=C
	INHIBITION X GROUP	More affected by load on control in F	n.s.
	RECALL X GROUP	-	F<C; F<TO with R2; R3; R4
	STIMULUS X GROUP	-	F<C; F<TO with N
	INHIB X REC X GROUP	In F LI>HI also with fewer items to recall	n.s.
	INHIB X STIM X GROUP	-	n.s.
	REC X STIM X GROUP	-	n.s.
	INHIB X REC X STIM X GROUP	-	n.s.

Key: F=Frontal participants; TO=Temporo-occipital participants; C=Controls; LI=Low Inhibition; HI=High Inhibition; R1, R2, R3, R4=1 item to recall, 2 items to recall etc.; W=Words (i.e. nouns); N=Numbers; > = better performance (i.e. more items recalled or fewer errors); < = worse performance (i.e. fewer items recalled or more errors); n.s. = not significant; - = no prediction made

In all groups, the performance decreased with an increase of the load on the inhibitory demand (i.e. the number of items in the list to suppress and not recall) and the memory load (i.e. the number of items to be recalled). The difference in performance between low and high inhibition was only significant when the load on maintenance was high (i.e. with three or four items to recall). This suggests that there is a trend for participants to be affected by the load on inhibitory processes when high demands are also made on the memory system.

The prediction that performance on both recall and inhibition of irrelevant information would be more affected by load on control processes in people with frontal lobe lesion compared with their controls were not supported by the data. In contrast, it was found that performance on both recall and inhibition was affected by load on maintenance processes: the difference between the frontal group and the other two groups was only evident when the load on the memory system was higher (i.e. with more than one item to recall). This suggests that in patients with frontal lobe damage control processes are impaired (Luria, 1966; 1969; Shallice, 1982) as well as maintenance processes. It also suggests that patients with a frontal lobe damage are more sensitive than others to demands on the maintenance processes. Surprisingly, however, such sensitivity to load on memory processes was not found for the controlling aspect of the updating task (requiring the participant to inhibit an increasing amount of irrelevant information).

5.4.2. Overall WM effects

The same main effects observed in a group of healthy adults investigated in chapter two, were expected for this study. These are illustrated in the "Predictions" section of Table 5.7, together with the results found. However, the results from the current data are mixed in this respect. This was partly confirmed by the results. Overall, the participants in this study were sensitive to load on control processes at lower levels of load on maintenance.

Table 5. 7: Updating task - Overall effects - predictions and results

		PREDICTIONS	RESULTS
RECALL	INHIBITION	LI>HI	LI>HI
	RECALL	Quadratic decrease	Quadratic decrease
	STIMULUS	W>N	W>N
	INHIB X RECALL	LI>HI with R4	LI>HI with R3; R4
	INHIB X STIMULUS	n.s.	n.s.
	RECALL X STIMULUS	W>N with R4	W>N with R4
	INHIB X REC X STIM	n.s.	n.s.
SAME LIST INTRUSIONS	INHIBITION	LI>HI	LI>HI
	RECALL	n.s.	Linear decrease
	STIMULUS	n.s.	N>W
	INHIB X RECALL	n.s.	LI>HI with R4
	INHIB X STIMULUS	n.s.	LI>HI with W
	RECALL X STIMULUS	n.s.	n.s.
	INHIB X REC X STIM	n.s.	n.s.
PREVIOUS LIST INTRUSIONS	INHIBITION	n.s.	LI>HI
	RECALL	Quadratic decrease	Quadratic decrease
	STIMULUS	W>N	W>N
	INHIB X RECALL	n.s.	LI>HI with R4
	INHIB X STIMULUS	n.s.	LI>HI with N
	RECALL X STIMULUS	W>N with R3 and R4	W>N with R4
	INHIB X REC X STIM	n.s.	With W: LI=HI With N: LI>H with R4
INVENTIONS	INHIBITION	n.s.	LI>HI
	RECALL	Linear decrease	Quadratic decrease
	STIMULUS	W>N	W>N
	INHIB X RECALL	n.s.	n.s.
	INHIB X STIMULUS	n.s.	LI>HI with N
	RECALL X STIMULUS	W>N with R4	W>N with R2, R3, R4
	INHIB X REC X STIM	n.s.	n.s.
OMISSIONS	INHIBITION	LI>HI	LI>HI
	RECALL	Quadratic decrease	Quadratic decrease
	STIMULUS	n.s.	N>W
	INHIB X RECALL	n.s.	LI>HI with R3; R4
	INHIB X STIMULUS	n.s.	n.s.
	RECALL X STIMULUS	W>N with R4	n.s.
	INHIB X REC X STIM	n.s.	With W: LI>HI with R3;R4 With N: LI>HI with R4

Key: LI=Low Inhibition; HI=High Inhibition; R1, R2, R3, R4=1 item to recall; 2 items to recall etc.; W=Words (i.e. nouns); N=Numbers; > = better performance (i.e. more items recalled or fewer errors); < = worse performance (i.e. fewer items recalled or more errors); Decrease= decrease in performance (i.e. fewer items recalled or more errors)

Other differences from the overall results expected from the performance of healthy adults, were found in the production of errors. In fact, the performance of this group was very similar to the performance of the group of adults and elderly participants (with low education) presented in chapter three. For example, in the production of same list intrusion errors, whilst an effect of load on control processes is evident, the occurrence of this kind of error in the overall group is modulated by the load on maintenance processes and by the type of stimulus to be recalled (with more errors produced when recalling words than when recalling numbers). These effects interacted with one another: the effect of load on control processes was only present in this group when the highest demands were posed on the maintenance process, and only when recalling words.

When examining previous list intrusion errors, the same effects of load on maintenance and of stimulus type as observed in chapter two were found. In addition, the effect of load on control processes is similar to that observed in chapter three, indicating that greater number of errors of this a kind were produced with higher load on control processes. This suggests that such an effect may have also been present in the healthy adults (chapter two), but did not reach statistical significance because of the relatively small number of participants investigated. In the production of invention errors, an expected effect of load on control processes was found. This effect is similar to that observed in the overall group of participants with DAT and their controls (chapter four). This could be due to the performance of the frontal group, but other results suggest a contrasting explanation (e.g.. no significant difference was found between groups in the effect of load of control processes).

A further interesting difference was found in the quality of omission errors: unlike the group of adult and elderly healthy participants (chapter two and three), frontal participants produced a greater number of omission errors when recalling words than when recalling numbers. This is similar to the pattern observed with DAT participants (chapter four).

5.4.3. Performance on numerical and calculation tasks

Another aim of this study was to investigate whether there are any differences between patients with frontal lobe damage and their controls on numerical and calculation tasks. Complex mental calculation requires abilities like holding and manipulating numbers in STM, the application of the appropriate algorithm, the retrieval and temporary storage of intermediate results, and the application of arithmetical rules. Therefore this process requires attentional control and WM processes (e.g. updating) and these were expected to be impaired in people with frontal lobe damage (Baddeley, 1986). The findings of the present study confirm this prediction. Moreover, the findings support the idea of what was described by Ardila and Rosselli (2002) as "frontal acalculia". The authors propose that patients with prefrontal lobe damage show difficulties in mental operations, consecutive operations (especially backwards) and multi-step numerical problems. The complex mental calculation tasks used in this study required such abilities and were performed poorly by participants with frontal lobe damage. In accordance with the predictions, the frontal group found it harder to perform operations at all levels of load on control processes (i.e. with all conditions of carrying and borrowing). This suggests that this group finds it difficult to perform calculations that may be relatively simple for healthy controls and those with a posterior damage. This was evident with both visual and verbal presentation, suggesting that the effect was not related solely to load on the PL, which is suggested to be involved in the temporary storage of addends when performing a mental calculation (Furst & Hitch, 2000; Noel, Desert, Aubrun, & Seron, 2001). The data also suggest that only with subtraction problems there was an advantage of visual presentation over verbal presentation, suggesting that subtraction may pose a higher load on both PL and CE whereas addition may be less taxing on the PL. Interestingly, the differences in performance between frontal and posterior groups are evident with low and intermediate, but not high, load on control processes, suggesting that at the latter level the two groups with brain damage perform similarly. This suggests a non-specific effect of brain damage on calculation performance.

Other interesting results are that in the overall sample studied, performance on addition problems was found to be better than performance on subtraction problems, in particular under more taxing conditions for control processes. A further investigation of the effects of presentation showed that overall the frontal group of performed below both control groups. Furthermore, the posterior group performed worse than the group of healthy controls. This could again be attributed to a non-specific effect of brain damage on performance. However, this does not explain the difference between frontal and posterior group.

An alternative interpretation of these results follows from Dehaene's triple-code model (Dehaene, 1992; Dehaene & Cohen, 1997; Cohen & Dehaene, 2000). The model posits that because addition is taught verbally and stored as verbal representations, the use of this operation in the context of complex mental calculation is not hampered by verbal presentation. Subtraction, on the other hand, requires semantic elaboration and the use of strategies, and in the context of complex mental calculation, verbal presentation can be a disadvantage (because of the additional load on the PL). The expected difference in the transcoding tasks, (such as intrusions of the source code in the target code (Kessler & Kalbe, 1996)) was not present in the data, but a difference was evident between the frontal group and healthy controls when writing Arabic numerals to dictation and in transcoding from the Arabic to the verbal code. The latter may be explained by a difficulty of the frontal group in transcoding an automatic representation of a number as an Arabic numeral into a verbal format. It is arguable, assuming that this kind of error in the frontal group is due to failure of control processes, that the presence of the numeral in Arabic format on the piece of paper would interfere with the production of the numeral in verbal format, causing a drop in performance. In the writing to dictation task, the phonological representation of the number-word might interfere with the production of the Arabic representation of the numeral, but this does not explain why this effect was not found in the other conditions (i.e. writing number words to dictation and transcoding from the verbal to the Arabic code). Contrary to expectations, a difference was found between groups in performance on the arithmetical facts.

It is of note, however, that the differences between groups were due to the poor performance of a very limited number of participants in the frontal group and therefore these results may not be generalizable to population with frontal lobe damage. Moreover, the task was designed to be a brief screening tool and it would therefore be interesting to investigate transcoding processes in greater detail, using specifically designed tests

5.4.4. Working Memory and Calculation

A final aim of this study was to investigate the relationship between numerical and calculation impairments in frontal lobe patients and the functioning of WM, and specifically to particular components of WM. The prediction was that this group of patients may have difficulties in monitoring arithmetical procedures, possibly because of an inability to update relevant information and inhibit no longer useful information at different stages of calculation. According to this idea, the calculation system would be affected by this WM impairment earlier in frontal patients than in healthy participants because of the greater load on executive functions and the higher demand of monitoring it requires. In order to test this, regression analyses were conducted in the three groups in order to assess how much of the variance in the calculation tasks was explained by the performance on the WM tasks. The results of these analyses show that the relationship between number tasks and maintenance processes in the updating tasks was only significant for people with brain damage (F and TO). This suggests that people with brain damage require greater maintenance resources from WM in order to perform tasks that are automatic for healthy controls.

It is also of note that when investigating the performance of the groups on the digit span backwards task, the processes involved in this task can explain a great portion of the variance found in the calculation tasks with verbal presentation. This suggests that the maintenance and control processes required to perform the digit span task (backwards) are similar to those involved in complex mental calculation in both healthy controls and participants with brain damage. Interestingly, for the group of healthy controls, the processes involved in the digit span backwards task explain a great portion of the variance found in the calculation tasks with visual presentation as well. This was not found for the groups with brain damage, suggesting that following brain damage, participants use different processes in order to perform complex mental calculations where the operands are visible for the time needed to solve the problem. Further work is needed to understand what these processes would be. This provides an interesting avenue for further work.

In summary, the data from the present study add to our knowledge of the effects of frontal lobe damage on WM processes. In particular it adds to the understanding of maintenance and control processes. The data confirmed a decline in CE as a consequence of frontal lobe damage. In particular, people with a lesion to the frontal lobes present with affected maintenance and control processes. Moreover, the data presented in this chapter also adds to the understanding of calculation processes and how these are affected by frontal lobe damage. The group of participants with frontal lobe lesion studied in this chapter, in fact, performed poorly on the complex mental calculation tasks, even when solving problems quite easy to perform for healthy controls. Furthermore, the results suggest that people with a brain damage (both frontal and posterior) need to use more maintenance resources from WM to perform operations relatively easy for healthy controls. However, it is important to remember that this was a preliminary study and that no definite conclusions can be drawn by these preliminary data. What can be definitely concluded is that the groups studied in this chapter can provide very useful information on the functioning (and malfunctioning) of the WM system and that therefore further research should focus on these groups. The implications of these findings and of the findings examined throughout the thesis will be discussed in the final chapter.

CHAPTER 6: GENERAL DISCUSSION

The aim of this series of experiments was to examine the role of working memory (WM) in various numerical tasks. Intuitively, one would assume that WM is involved in numerical or calculation tasks, as they usually require to hold information in memory and manipulate it in order to get to a solution. However, the current literature is equivocal on this subject. Importantly, previous studies have not carefully distinguished between the hypothesised independent subcomponents of WM that have been the focus of this thesis: control and maintenance processes. These processes were explored in two ways: by using an "updating task" which taps both control and maintenance processes concurrently; and secondly, groups of participants were investigated who were expected to show relatively selective impairments of these two components: older adults, DAT, and frontal lobe patients.

On the basis of the results, it is possible to evaluate: the hypotheses of independent subcomponents of WM; their role in remembering words and numbers; and their relationship with calculation ability.

6.1. Summary of experiments

The first aim of the studies presented in this thesis was to gain a greater understanding of specific processes of the central executive of WM. To do this, the ability to update relevant information (considered here as a measure of the capacity of WM) and the ability to inhibit irrelevant information (considered as a measure of control processes in the CE) were investigated. To assess updating and inhibiting abilities, various WM tasks were used which assess: the capacity of the PL; the processing capacity of WM; and the control processes in the CE. In addition to established tests, a novel test was developed which was based on an updating task previously used by Palladino et al. (2001). The processing capacity of WM was conceptualised as the amount of information recalled after being held and manipulated in WM (maintenance). This concept is similar to what Broadbent (1958) called "channel capacity", and Cowan (1995) called the "capacity of the focus of attention". The control processes of the CE were conceptualised as the amount of information to be suppressed according to a given criterion (inhibition). This concept is similar to the selective filter in Broadbent's (1958) conceptualisation, and the control of the direction of attentional focus in Cowan's (1995) conceptualisation. In the experiments reported throughout the present work, the WM abilities of various groups of participants have been examined, in order to investigate possible dissociations between components of the WM system as conceptualised by Baddeley (1986), particularly between those processes believed to be served by the CE. These processes are conceptualised as the storage and processing of the focus of attention in Cowan's (1995) model.

In the first experimental chapter (chapter 2) the updating task was used with healthy participants in order to investigate the relationship between simple span tests and the updating task, and to test the prediction that the updating task was indeed measuring maintenance and control processes. Chapter 3 investigated differences in WM processes at different stages of the life span. The impact of Alzheimer's type dementia (DAT) at the early stages and of frontal brain damage on WM processes was investigated in chapters 4 and 5, respectively.

A central hypothesis of this thesis is that WM would be differentially affected by normal aging, dementia of the Alzheimer's type and frontal brain damage was investigated by investigating performance on the updating task in participants from these populations. The predictions were that: in normal ageing maintenance would be reduced but control processes would be spared; in senile dementia both processes would be impaired; and with frontal damage only control processes would be affected, as suggested by Baddeley (1986).

Moreover, given the difficulties reported in the literature of patients with DAT or frontal lobe damage with numerical and calculation tasks, and the involvement of WM in some of these tasks, chapter 4 and 5 investigated the impact of these conditions on the ability to perform complex mental calculations and the relationship between these abilities and the functioning of WM processes.

6.2. Theoretical implications of the major findings

As Morris and Jones (1990) have suggested, it is difficult to study the central executive in isolation from the other subsystems, because of its ability to re-use its resources very rapidly in order to coordinate complex cognitive processes. Moreover, there is some confusion in the literature on WM concerning terminology: often the distinction between the activation required to manipulate information in WM and the portion of memory holding that information is unclear. In 1986, Baddeley drew a distinction between control processes and processing capacity of the CE, and made predictions about how they could be selectively affected by various conditions (similar to those studied in the present thesis). Baddeley (1993) later abandoned the concept of a storage capacity of the CE, which left some confusion about the limits of the CE, in terms of the amount of information that can be manipulated at any one time and what processes this depends on. The scope of this thesis was to investigate the WM system, and in particular at the CE, to identify the different processes that may be involved in its functioning. In particular, the distinction between capacity and processing functions was examined. This is easier to conceptualise within Cowan's framework (Cowan, 1995; 1999; 2001; 2003; 2004; 2005), which posits that the distinction between the focus of attention and awareness and the amount of activated information is very important; and that WM must involve both activation and awareness (Cowan, 1999). Cowan's definition of WM is functional in that the processing mechanisms that contribute to a memory task are considered to collectively make up WM.

6.2.1. Control and maintenance processes in Working Memory

In order to analyse the distinction between capacity and processing functions, the WM system was investigated by using an updating task devised to place variable demands on maintenance and control processes. The capacity of the central executive, conceptualised here as the amount of information kept activated in order to be manipulated (i.e. "updated", in the present study), should be reflected in the amount of information effectively recalled in the updating task. It was hypothesised that performance on the updating task would be affected by the demands of the task on both storage (i.e. how much information had to be held) and processing (i.e. how much information that was presented had to be inhibited in order to successfully complete the task). This was confirmed by the results. The pattern of decrease in recall performance with increased load on maintenance suggests that there is a threshold for the number of items that WM can hold and manipulate efficiently at any one time. Beyond that threshold, performance drops abruptly. These results are consistent with the idea of a storage capacity of the central executive and also with suggestions that success in remembering relevant and suppressing irrelevant information in WM is related to the availability of resources to the WM system (Engle et al., 1992; Conway et al., 1999). An interaction between capacity and processing, was also found in the study: recall performance was poorer with a high versus low load on control processes when the load on maintenance was highest (arguably when the system reached its capacity limits). This suggests that, when the information to manipulate does not exceed a threshold, the CE has enough resources to efficiently hold, manipulate and inhibit information, even with a considerable amount of information to inhibit. Beyond that threshold, if the resources available to both processes are taxed, the CE becomes more sensitive to the load on control processes.

In the present research the processing functions of the central executive (control processes in Baddeley's early conceptualisation (1986), or "activation" in Cowan's (1988) interpretation) were construed as the ability to successfully inhibit irrelevant information. This was measured using the production of same list intrusion errors. If this variable was a valid measure of the functioning of the suppression/inhibition mechanism of the CE, it would be expected that it would only be affected by the load on control processes. This was indeed confirmed by the results of the study.

A further prediction of the study was that recall of numbers would be more difficult than words because of their higher semantic and syntactic complexity. This was hypothesised to have an impact on the processing capacity of the CE but not on the activation itself, and therefore no difference was expected in the production of same list intrusion errors. These predictions were confirmed by results that showed greater previous list and invention errors when recalling numbers than when recalling words. This effect was present when the load on maintenance process was higher. If there is, as suggested above, a threshold for the number of items that WM can hold and manipulate efficiently at once, beyond that threshold the drop in performance is more evident when the material to be recalled is more complex and similar in nature (i.e. two-digit numbers, as discussed in chapter 2), as this would pose additional load on the maintenance processes, decreasing performance even further. An additional factor that may explain the results is the stimulus word length, in accordance with Baddeley (1975). In fact, the numbers used in the updating task contained on average more syllables than the words.

From the data described in this thesis, it emerges that CE has both capacity and processing functions and that there is a limit to the amount of information that can be manipulated at any one time by the WM system. Furthermore, the capacity of the CE is different from the capacity of the slave systems (such as the PL).

6.2.2. Conditions affecting Working Memory

If activation (i.e. control processes) and the amount of activated information (i.e. processing capacity), are distinct it should be possible to find dissociation between their functioning. In order to verify this, the present research investigated the predictions made by Baddeley (1986), before abandoning the concept of a storage capacity of the central executive (Baddeley, 1993). The predictions that were tested were therefore that in normal ageing maintenance would be reduced but control processes would be spared; in senile dementia both processes would be impaired and with frontal lesions only control processes would be affected.

6.2.2.1. Normal ageing

A decrease in processing capacity with no concomitant decrease in control processes were indeed found with ageing, as expected. The decrease in processing capacity appears to be a gradual process as it was found in mid-aged adults and seems to continue into older age. This result is consistent with Baddeley's (1986) suggestion that ageing provokes a decrease in the "total processing capacity" of the CE and challenges Van der Linden et al.' (1994) claim that the reduction of CE resources with aging is due to a reduction in the processing functions of the CE but not related to its storage. The results of the present research on the effects of ageing on WM also dispute Hasher and Zacks' (1988) suggestion that elderly adults would have difficulty in inhibiting or suppressing irrelevant or no longer relevant information. Interestingly, however, the results of the present thesis suggest that in the first half of the life span the efficiency of control mechanisms of WM reduce when high demands are placed on this process. This stabilises over time, which may explain why the effect was not found when comparing adults with elderly. The results found in the updating task match those found in the span tests: a gradual decrease in storage capacity with ageing, already noticeable in middle-aged adults, and a reduction of control processes (found in the digit span backwards) around the middle of the life span, that seems to plateau with further ageing. The latter finding gives partial support to the suggestions of Van der Linden et al. (1994) and Hasher and Zacks (1988), although the changes these authors argue to occur in older age, actually seem to emerge much earlier in life. The present results suggest that aspects of WM are differentially affected by the aging process: processing capacity gradually decreases with age; and control processing decreases in the first half of the life span and then stabilise. Additionally, there is a suggestion that to a certain extent the capacity of the PL is also affected by ageing because the data shows a reduced length effect in elderly compared to younger adults.

6.2.2.2. DAT

In DAT, processing capacity was reduced compared to a group of age-matched and younger controls. The typology of errors produced by DAT (inventions and omissions) suggests that memory processes are generally impaired in this group and the failure to recall correct information manifests as either the omission of a response or a "false recall" (i.e. recall of never presented items). The latter could be considered a form of provoked confabulation, which, as suggested by Kopelman (1987; 2002), may reflect a normal response to a faulty memory. Alternatively it could reflect a deficit of some aspect of executive function: a self-monitoring deficit; a failure to inhibit memory errors; or frequent perseverations (Shapiro, Alexander, Gardner, & Mercer, 1981). If a CE deficit in DAT is assumed, the possibility that the increase of invention errors was due to a failure to inhibit memory errors seems likely, suggesting a deficit in control processes. This idea is supported by the effect of load on control processes in the production of invention errors. However, the possibility that the invention errors are secondary to the memory deficit itself (Kopelman, 2002) and not the reflection of an executive dysfunction cannot be discarded.

The results also suggest that in DAT progressively more control resources are required, even for tasks that are automatic for healthy elderly adults (Spinnler, 1991). Load on maintenance processes was more detrimental to recall performance in people with DAT than controls. Load on control processes was more detrimental to both the ability to recall and to inhibit irrelevant information.

Moreover, in the DAT group, the effect of load on control processes on recall performance was present at lower levels of load on maintenance than in the other two groups. This pattern of results supports the idea that people with DAT are sensitive to tasks in which CE involvement is particularly high (Jorm, 1986). These findings, together with the results of the span task showing a decline in the PL functioning partly due to the aging process (as shown with elderly controls) and partly to the dementing process are compatible with the suggestion that DAT can affect several components of WM (i.e. the phonological store, articulatory rehearsal system and CE mechanism) but that not necessarily all aspects of CE are affected (Collette et al., 1998). In fact, contrary to the predictions, there is no clear evidence from this study that in DAT the control processes themselves are impaired, as demonstrated by the lack of a difference between groups in the recall of to-be-inhibited information. It can only be assumed that the processing capacity of the CE as well as the PL are affected, as demonstrated by differences between groups in maintenance processes. This suggests a dissociation between control processes and processing capacity, suggesting that these elements of WM are at least partially separable. However, the evidence does not allow a distinction between WM processes in normal ageing and DAT, in accordance with Baddeley (1986), as both groups displayed a decrease in control processes compared to their matched controls. Therefore, it is not possible to rule out the possibility that control processes and processing capacity are simply different aspects of the same process (i.e. CE).

6.2.2.3. Frontal lobe damage

In this group, impairment in control processes were expected without concomitant impairment in processing capacity (Baddeley, 1986). This was not supported by the data, as the group with frontal lobe damage showed an impaired recall performance, a measure of the processing capacity of the central executive, as well as inhibition. Moreover, performance on both recall and inhibition was affected by load on maintenance processes and not on control processes. This suggests that patients with frontal lobe damage are more sensitive than those without such damage to demands on maintenance processes, which implies that the capacity of their central executive is reduced.

Therefore, it would seem that not only the control processes, but also the overall processing capacity of the CE is impaired by a frontal lesion. This is in contrast to Baddeley's (1986) suggestion that in the dysexecutive syndrome the control processes are deficient but the overall processing capacity is intact. It is of note, however, that in the present study the participants with frontal lobe damage did not show signs of dysexecutive syndrome on standard tests. It may therefore be that lesions leading to dysexecutive syndrome affect more selectively the control processes of WM than the lesions of the participants to this study. Once again the data do not fit with the predictions on the proposed dissociation between processing capacity and control processes. This could again suggest that control processes and processing capacity are indeed different aspects of a same process.

6.2.3. Working Memory and Calculation

In order to investigate the relationship between WM and mental arithmetic, performance on the updating task and measures of numerical and calculation processing were investigated in the groups of participants with neurological damage (i.e. with DAT and frontal lobe damage). They were chosen because these groups were reported in the literature as having problems in WM as well as in mental arithmetic (see Chapter 4 and Chapter 5).

The present study did not find the expected differences in the numerical and calculation tasks (i.e. transcoding tasks and complex mental calculation) between people with DAT and controls. However, the relationship between number tasks and updating tasks, i.e. involving both maintenance and control processes, was only significant for people with DAT. This suggests that, although the performance on calculation does not seem to be affected by the dementia, at least at this initial stage, people with DAT require more WM maintenance and control processes in order to perform tasks that are relatively automatic for healthy elderly adults.

In contrast, the prediction that participants with frontal lobe damage would perform poorly in complex mental calculation compared to their controls was confirmed, in accordance with Baddeley (1986) and Ardila and Rosselli (1990). The results indicate that this group of participants have difficulty with calculations that are relatively simple for healthy controls. Moreover, this effect is evident with both visual and verbal presentation and therefore does not seem related to the amount of load on the PL, which is involved in the temporary storage of addends when performing a mental calculation (Furst & Hitch, 2000; Noel et al., 2001). Differences found in tasks of transcoding and arithmetic facts were due to a small number of participants and therefore the results may not be generalizable. The findings concerning the relationship between numerical and calculation tasks and WM tasks reflect the relationship between number tasks and maintenance processes in the updating tasks for people with frontal brain damage and the control group with posterior brain damage, but not the healthy controls. This indicates that people with brain damage, irrespective of their ability to perform numerical and calculation tasks, require more WM maintenance resources than healthy controls in order to perform tasks that are relatively automatic for the latter group.

6.3. Strengths and Limitations

The research in this thesis sought to test Baddeley's predictions about conceptualization of WM, using a wide range of experimental groups. Rigorous testing of his predictions shows some support, including large effects, but the support is not complete. The findings suggest the model may be inadequate, and other models , such as Cowan (1999)'s, may explain the data better. However, the experimental paradigm does not suit these models, and therefore, other experimental paradigms may be needed to test such models. This is an interesting area for future research.

6.3.1. Experimental Design

As discussed in chapter 2, the numbers used in the updating task contained on average more syllables than the words used. This is obviously a limitation of the study but it would have been very difficult to overcome, as the use of two-digit numbers (as opposed to one-digit numbers) was necessary in order to have a large number of different items, and also because they are more likely to occur in complex mental calculation. Moreover two digit numbers have a greater semantic and syntactic complexity (and similarity) than the words used in the study. This potential limitation of the study was necessary in order to have a large enough pool of number-words to be compared with the other words used for the updating task. A strength of this study is that the task has been used with a wide range of people and neurological conditions.

Detailed information on localization of the brain damage of the participants in the research was not available. Their inclusion in the study was based on their lesion profile as determined by the neurologist involved in the recruitment process. Therefore, evidence of the extent of their lesion cannot be demonstrated, and it is possible that the participants could have formed more of a heterogeneous group than assumed for these experiments. This may explain why there were within group differences, for example in some of the calculation tasks. In future work, it would therefore be important to gather more detailed information on the precise location of the lesion, and to create more homogeneous groups.

The participants with DAT were at the very early stages of the disease, and stronger effects may have been present in participants at a more advanced stage of dementia. However, this was not possible in the present study because of the complexity of some of the tasks used, which would have been impossible for individuals with severe cognitive impairment to understand and complete.

Another limitation of the study was that the groups investigated were relatively small (particularly the group with frontal lobe damage). Therefore the results would need to be replicated on a larger scale in order to make firm conclusions about such processes. Despite the limitations of sample size, this study led to interesting results in groups that had not been investigated before. Moreover, the differences found were strong, despite the relatively small pool of participants investigated. This could be a strength of the study.

6.4. Future Directions

Throughout this discussion, avenues for future work have been outlined. In addition, there are a number of ways in which the current research could be extended. An interesting development of this research would be to conduct a longitudinal study, in particular investigating the effects of ageing and DAT. A longitudinal study investigating the ageing process would control for inter-subject variability. This was not possible in the present research, as testing would be required at intervals of decades, in order to be theoretically useful. It would be more feasible, but nevertheless interesting, to observe the dementing process longitudinally. This would provide a clearer indication of performance on the cognitive processes of interest at various stages of DAT, as has been shown in the field of numerical processing using single case studies (Grafman et al., 1989; Girelli et al., 1999). This would also further our understanding of the fractionation of the relevant cognitive systems. For example, a longitudinal study on the degeneration of arithmetic functioning in a patient with semantic dementia has proven valuable in exposing patterns of dissociations between different number abilities (Cappelletti, Kopelman, Morton, & Butterworth, 2005).

A useful direction for future work with the updating task could involve performance assessment in other populations with frontal deficits, such as the transient effects found in extreme conditions (e.g. high altitude, diving or stress). This would be interesting, because such participants could be their own controls, under normal conditions. It would also be interesting to use the updating task with children with learning difficulties such as dyslexia, poor reading comprehension or dyscalculia in order to investigate the role of WM, and in particular updating, in these conditions. This would allow a more detailed investigation of the role of different WM processes in complex cognitive functions, such as reading and calculation.

In order to understand WM to a greater extent, an imaging study of participants while they perform the updating task may be useful. It would be interesting to compare it with other span tests that do not require updating, and observe which brain areas are involved in CE. It could be predicted that the dorsolateral prefrontal cortex (DLPFC) would be involved (Curtis & D'Esposito, 2003). Moreover parametric variation of memory load could be used to reveal the circuitry underlying verbal working memory, as suggested by Jonides et al. (Jonides, Schumacher, Smith, Lauber, Awh, Minoshima, & Koeppe, 1997).

6.5. Conclusion

In conclusion, the work presented here has provided new understanding of the complexity of WM. Furthermore, it has increased our knowledge of the complexity of the effects neurological conditions (e.g. DAT or frontal lesions) on complex cognitive functions such as WM and calculation. This body of work, combined with future work, helps to further our knowledge and understanding of a fundamental human function.

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APPENDICES

Appendix I

Span Tests

TESTING SESSION 1[238]

Digit span Forward and Backward:

DIGIT SPAN
FORWARD

Esempio: 7 -9 **4-2**							
	w	s	l		w	s	l
5-8-2	3	5	13	5-9-1-7-4-2-8	7	14	32
6-9-4	3	5	14	4-1-7-9-3-8-6	7	12	29
6-4-3-9	4	6	17	5-8-1-9-2-6-4-7	8	15	35
7-2-8-6	4	7	15	3-8-2-9-5-1-7-4	8	15	35
4-2-7-3-1	5	9	21	2-7-5-8-6-2-5-8-4	9	17	41
7-5-8-3-6	5	8	21	7-1-3-9-4-2-5-6-8	9	16	38
6-1-9-4-7-3	6	10	25	**Span avanti:**			
3-9-2-4-8-7	6	11	26				

BACKWARDS

Esempio: 7 -1-9 (9-1-7) **3-4-8 (8-4-3)**			
2-4	2	5-3-9-4-1-8	6
5-8	2	7-2-4-8-5-6	6
6-2-9	3	8-1-2-9-3-6-5	7
4-1-5	3	4-7-3-9-1-2-8	7
3-2-7-9	4	9-4-3-7-6-2-5-8	8
4-9-6-8	4	7-2-8-1-9-6-5-3	8
1-5-2-8-6	5	**Span indietro:**	
6-1-8-4-3	5		

[238] For all of the tasks administered, half participant were administered Testing session 1 first and half were administered Testing session 2 first.

Nouns 2-syllable span:

2 SILLABE SPAN

Esempio: CAPRA -ORSO SCUOLA -NODO			
	w	s	l
GAZZA -CUBO -PIPA	3	6	13
VASO -LUPO -STATUA	3	6	14
PALO -GIACCA -CANE -TORO	4	8	18
GUFO -PALA -DIGA -RANA	4	8	16
SECCHIO -NAVE -RAGNO -MULO -TOPO	5	10	24
GATTO -GHIRO -VELA -TALPA -FARO	5	10	23
CASA -VOLPE -GONNA -FUNE -TROTA -LEPRE	6	12	28
VERME -LUPO -PANE -CHIESA -AULA -ROSPO	6	12	28
BISCIA -GUFO -PALO -ORSO -VELA -NODO -VASO	7	14	30
SCUOLA -CANE -GAZZA -TOPO -CUBO -PIPA -DIGA	7	14	31
TALPA -CASA -TORO -VOLPE -FUNE -NAVE -STATUA -GATTO	8	16	37
RAGNO -PALA -FARO -RANA -MULO -TROTA -GHIRO -GIACCA	8	16	37
2 sillabe span:			

Proper names 3/5-syllable span:

NOMI PROPRI (3/5 SILLABE) SPAN

Esempio: ALESSANDRO -GIANPIERO PRISCILLA -ALESSANDRA			
	w	s	l
ALBERTO -ANNAMARIA -SIMONETTA	3	12	25
ELISABETTA -FERDINANDO -MARIELLA	3	12	28
GABRIELLA -PATRIZIA -GIOVANNI -BARTOLOMEO	4	15	35
ARMANDO -CARLOTTA -VALENTINA -GIANBATTISTA	4	14	36
FRANCESCA -ANNAGRAZIA -SILVESTRO -MARCELLO -GUGLIELMO	5	17	45
SEBASTIANO -GIANCARLO -ANASTASIA -GIUSEPPE -GRAZIELLA	5	18	45
MARINELLA -DAMIANO -GERTRUDE -ANTONELLA -FABRIZIO -GIANLUIGI	6	21	50
PIERSILVIO -RICCARDO -FLORIANA -RAFFAELLA -NICOLETTA -GIANFRANCO	6	21	54
GIANLUCA -FILIBERTO -MASSIMILIANO -GILBERTO -ALESSANDRA -FIORELLA -PRISCILLA	7	25	64
ELISABETTA -FERDINANDO -ALBERTO -BARTOLOMEO -GIOVANNICASSANDRA -GIUDITTA	7	26	62
GIANBATTISTA -ANNAMARIA -GABRIELLA -GIANPIERO -FRANCESCA -BRIGITTA -VALENTINA -SEBASTIANO	8	30	75
GIANLUIGI -ANNAGRAZIA -ANASTASIA -SILVESTRO -MARINELLA -PIERSILVIO -GUGLIELMO -SIMONETTA	8	32	74

TESTING SESSION 2

2-digit span:

2-DIGIT SPAN

Esempio: 71 -23 92-76			
	w	s	l
59-26-48	3	12	32
56-41-78	3	12	33
96-62-31-83	4	16	39
93-86-52-33	4	16	41
98-22-73-69-81	5	21	50
63-53-72-21-38	5	19	51
46-59-88-32-61-79	6	26	65
69-39-82-58-92-31	6	25	62
63-89-43-29-52-36-76	7	29	74
86-91-33-71-53-62-28	7	27	69
83-96-66-79-32-26-42-49	8	34	83
41-22-58-23-46-81-99-68	8	34	82

Proper names 2-yllable span:

NOMI PROPRI (2 SILLABE) SPAN

Esempio: CELSO-DINO MOIRA-LARA			
	w	s	l
DARIO -ELDA-INES	3	6	13
SARA -IGOR -FLAVIA	3	6	14
RITA -SANDRA -OMAR -ALDO	4	8	18
SIRO -ANNA -IRMA -REMO	4	8	16
GLENDA -MARTA -MAURO -DIEGO -UGO	5	10	24
GUIDO -LORIS-OLGA-MARCO-ADA	5	10	22
ELSA -PAOLO -VANDA -LISA -RENZO -SISTO	6	12	28
PIERO -LUCA -EMMA-FULVIA -LARA-WALTER	6	12	29
DARIO -DINO -LAURA -IGOR -ELDA-MOIRA -RITA	7	14	31
FLAVIA -OMAR -CELSO -ALDO -SARA -ANNA -IRMA	7	14	31
MAURO -INES -SIRO -GUIDO -OLGA -LISA -SANDRA -DIEGO	8	16	37
LORIS-ADA-MARTA -RENZO-UGO -MARCO -PAOLO -GLENDA	8	16	37

Nouns 3/5-syllables span:

3/5 SYLLABLES SPAN

Esempio: **COCCINELLA -CINGHIALE RINGHIERA -TERMOMETRO**			
	w	s	l
CANGURO -AEROPLANO -BOROTALCO	3	12	25
ELICOTTERO -PAPPAGALLO -CHITARRA	3	12	28
AUTOGRAFO -BATTELLO -SERPENTE -IPPOPOTAMO	4	15	35
CAVALLO -SOFFITTO -MOTOSCAFO -SCAR AFAGGIO	4	14	35
RACCHETTA -FRIGORIFERO -LOMBRICO -MARMOTTA -SCORPIONE	5	17	45
COCCODRILLO -FARFALLA -TELECAMERA -CAMMELLO -BERSAGLIO	5	18	46
BIBLIOTECA -GIRAFFA -CUCCHIAIO -TERMOMETRO -ANGUILLA -PANTEGANA	6	21	51
PETTIROSSO -SOGLIOLA -CRISTALLO -TELEGRAMMA -CANOCCHIALE - PINGUINO	6	21	56
MERLUZZO -ERMELLINO -RINOCERONTE -CINGHIALE -FRANCOBOLLO - RINGHIERA -CHITARRA	7	25	65
CANOCCHIALE -SANGUISUGA -CANGURO -PAPPAGALLO -CAVALLO - RACCHETTA -BATTELLO	7	24	62
COCCINELLA -TELEVISIONE -TERMOMETRO -SERPENTE -BERSAGLIO -SOFFITTO - BOROTALCO0IPPOPO TAMO	8	30	75
SCARAFAGGIO -TERMOSIFONE -AEROPLANO -LOMBRICO -FRIGORIFERO - FARFALLA -ANGUILLA -CUCCHIAIO	8	28	74

Appendix II

Updating Task

TESTING SESSION 1

Updating (nouns):

UPDATING PAROLE (1)

ESEMPIO

1) Ricordare l'animale piu' piccolo:

GIAGUARO	
ZANZARA*	

2) Ricordare l'oggetto piu' piccolo:

FURGONE	
PADELLA*	
ALTARE	

3)Ricordare i 2 animali piu' piccoli:

ARAGOSTA*	
MUCCA	
USIGNOLO*	

TEST

4) Ricordare l'oggetto piu' piccolo:

DAMIGIANA	
CARAMELLA*	

5) Ricordare l'animale piu' piccolo:

MAIALE	
ELEFANTE	
TARTARUGA*	
FOCA	

6) Ricordare i 2 oggetti piu' piccoli:

VASCA	
RUBINETTO*	
CONFETTO*	

7) Ricordare i 2 animali piu' piccoli:

GRANCH IO*	
LUPO	
CERVO	
VIPERA*	
CANGURO	

8) Ricordare i 3 oggetti piu' piccoli:

BICCHIERE*	
INCUDINE*	
TRAVE	
COLTELLO*	

9) Ricordare i 3 animali piu' piccoli:

CAPRA	
CORVO*	
SCORPIONE*	
SQUALO	
CICALA*	
GIRAFFA	

10) Ricordare i 4 oggetti piu' piccoli:

MONETA*	
DIVANO	
LANTERNA*	
COPERCHIO*	
CALAMITA*	

11) Ricordare i 4 animali piu' piccoli:

CINGHIALE	
LUCERTOLA*	
PECORA	
LUMACA*	
CONIGLIO*	
CAMMELLO	
SOGLIOLA*	

Updating (numbers):

UPDATING NUMERI (1)

ESEMPIO

12) Ricordare il numero piu' piccolo:

52*	
94	

13) Ricordare il numero piu' piccolo:

87	
79	
45*	

14) Ricordare i 2 numeri piu' piccoli:

66	
46*	
28*	

TEST

15) Ricordare il numero piu' piccolo:

29*	
93	

16) Ricordare il numero piu' piccolo:

76	
64	
88	
36*	

17) Ricordare i 2 numeri piu' piccoli:

57*	
85	
49*	

18) Ricordare i 2 numeri piu' piccoli:

44*	
68	
72	
96	
32*	

19) Ricordare i 3 numeri piu' piccoli:

83	
25*	
59*	
37*	

20) Ricordare i 3 numeri piu' piccoli:

48*	
92	
22*	
78	
84	
56*	

21) Ricordare i 4 numeri piu' piccoli:

89	
47*	
35*	
27*	
53*	

22) Ricordare i 4 numeri piu' piccoli:

26*	
42*	
74	
34*	
62	
98	
54*	

TESTING SESSION 2

Updating (nouns):

UPDATING PAROLE (2)

ESEMPIO

34) Ricordare l'oggetto piu' piccolo:

PADELLA*	
FURGONE	

35) Ricordare l'animale piu' piccolo:

MUCCA	
GIAGUARO	
ARAGOSTA*	

36) Ricordare i 2 oggetti piu' piccoli:

DAMIGIANA	
COPERCHIO*	
MONETA*	

TEST

37) Ricordare l' animale piu' piccolo:

FARFALLA*	
CAVALLO	

38) Ricordare l' oggetto piu' piccolo:

DOCCIA	
SCAFFALE	
STATUA	
CUCCHIAIO*	

39) Ricordare i 2 animali piu' piccoli:

ANATRA*	
ZEBRA	
TARTARUGA*	

40) Ricordare i 2 oggetti piu' piccoli:

CRAVATTA*	
TAPPETO	
TAVOLO	
EDICOLA	
LUCCHETTO*	

41) Ricordare i 3 animali piu' piccoli:

CERVO	
CICALA*	
GABBIANO*	
GRANCHIO*	

42) Ricordare i 3 oggetti piu' piccoli:

RUBINETTO*	
MACCHINA	
PILLOLA*	
TRAVE	
MATERASSO	
INCUDINE*	

43) Ricordare i 4 animali piu' piccoli:

SQUALO	
CORVO*	
LUCERTOLA*	
LUMACA*	
VIPERA*	

44) Ricordare i 4 oggetti piu' piccoli:

CONFETTO*	
COLTELLO*	
VASCA	
CALAMITA*	
FINESTRA	
TETTO	
LANTERNA*	

Updating (numbers):

UPDATING NUMERI (2)

ESEMPIO

23) Ricordare il numero piu' piccolo:

79	
23*	

24) Ricordare il numero piu' piccolo:

94	
52*	
86	

25) Ricordare i 2 numeri piu' piccoli:

45*	
87	
39*	

TEST

26) Ricordare il numero piu' piccolo:

66	
24*	

27) Ricordare il numero piu' piccolo:

75	
99	
49*	
67	

28) Ricordare i 2 numeri piu' piccoli:

74	
48*	
26*	

29) Ricordare i 2 numeri piu' piccoli:

37*	
65	
83	
53*	
77	

30) Ricordare i 3 numeri piu' piccoli:

38*	
56*	
78	
42*	

31) Ricordare i 3 numeri piu' piccoli:

63	
47*	
33*	
89	
25*	
97	

32) Ricordare i 4 numeri piu' piccoli:

28*	
82	
54*	
46*	
34*	

33) Ricordare i 4 numeri piu' piccoli:

73	
35*	
69	
27*	
55*	
95	
43*	

Appendix III

Numerical tasks

TESTING SESSION 1

Reading and Writing Numerals (Arabic to Verbal):

TRANSCODING (Arabico → Verbale)

Stimoli	Risposta	
	Lettura	Scrittura
ES: 2		
5		
80		
1		
4		
56		
60		
1000		
18		
706		
8		
13		
520		
34		
5207		
3		
6		
100		
2139		
627		
1024		
	Totale: /20	Totale: /20

Writing numerals to dictation:

SCRITTURA NUMERI ARABI (dettato)
(1d=1 -digit; Te=teens; 2d=2 cifre; 2_0=2 cifre con 0; 3d=3 cifre; 3_0=3 cifre con 0; 4d=4 cifre; 4_0=4 cifre con 0)

Stimoli	Categoria	Risposta	Punteggio
7	1d		
320	$3_{0\text{-}3rd}$		
6324	4d		
903	$3_{0\text{-}2nd}$		
4109	$4_{0\text{-}3rd}$		
90	2_0		
718	3d		
56	2d		
2240	$4_{0\text{-}4th}$		
15	Te		
7072	$4_{0\text{-}2nd}$		
300	3_0		
			Totale: /12

Writing words to dictation:

SCRITTURA PAROLE (dettato)

Stimoli	Risposta	Punteggio
BIVIO		
FRIGORIFERO		
METALMECCANICO		
PALCOSCENICO		
CONTACHILOMETRI		
BILANCIA		
ACCENDISIGARI		
FRANCOBOLLO		
PARALLELEPIPEDO		
AUTOBUS		
TERGICRISTALLO		
TRIFOGLIO		
		Totale: /12

TESTING SESSION 2

Reading and Writing Numerals (Verbal to Arabic):

TRANSCODING (Verbale → Arabico)

Stimoli	Risposta	
	Lettura	**Scrittura**
ES: due		
cinque		
ottanta		
uno		
quattro		
cinquantasei		
sessanta		
mille		
diciotto		
settecentosei		
otto		
tredici		
cinquecentoventi		
trentaquattro		
cinquemiladuecentosette		
tre		
sei		
cento		
duemilacentotrentantanove		
seicentoventisette		
milleventiquattro		
	Totale: /20	**Totale: /20**

Writing number-words to dictation:

SCRITTURA PAROLE -NUMERO (dettato)
(1d=1 -digit; Te=teens; 2d=2 cifre; 2_0=2 cifre con 0; 3d=3 cifre; 3_0=3 cifre con 0; 4d=4 cifre; 4_0=4 cifre con 0)

Stimoli	Categoria	Risposta	Punteggio
7	1d		
320	$3_{0\text{-}3rd}$		
6324	4d		
903	$3_{0\text{-}2nd}$		
4109	$4_{0\text{-}3rd}$		
90	2_0		
718	3d		
56	2d		
2240	$4_{0\text{-}4th}$		
15	Te		
7072	$4_{0\text{-}2nd}$		
300	3_0		
			Totale: /12

Appendix IV

Calculation tasks

TESTING SESSION 1

Arithmetical Facts (Addition and Subtraction):

FATTI ARITMETICI SEMPLICI
(1st addend: N=bigger;n=smaller; result:M=>10, m=<10; R=rule)

ADDIZIONI

Stimoli	Risultato	Categoria	Risposta	RT	Punteggio
3+1	**4**	**ES** (N-m)			
2+4	**6**	**ES** (n-m)			
0+9	9	N-m-R			
6+5	11	N-M			
1+2	3	N-m			
9+4	13	N-M			
3+2	5	N-m			
4+6	10	n-M			
3+5	8	n-m			
8+6	14	N-M			
5+0	5	N-m-R			
2+6	8	n-m			
					Totale: /10

SOTTRAZIONI

Stimoli	Risultato	Categoria	Risposta	RT	Punteggio
2-1	**1**	**ES**			
5-2	**3**	**ES**			
3-0	3	N-m-R			
6-4	2	N-m			
8-7	1	N-m			
7-3	4	N-m			
9-6	3	N-m			
7-5	2	N-m			
6-3	3	N-m			
7-0	7	N-m-R			
5-3	2	N-m			
8-2	6	N-m			
					Totale: /10

Jackson and Warrington test (Addition):

JACKSON TEST
(Carrying: 0c, 1c, 2c)

ADDIZIONI

Stimoli	Risultato	Categoria	Risposta	RT	Punteggio
9+6	15	1c			
11+8	19	0c			
15+13	28	0c			
18+7	25	1c			
68+34	102	2c			
99+22	121	2c			
123+29	152	1c			
43+78	121	2c			
68+47	115	2c			
89+133	222	2c			
58+147	205	2c			
173+68	241	2c			
128+149	277	1c			
244+129	373	2c			
				Totale:	**/14**

Complex mental calculation (Subtraction):

CALCOLO MENTALE

SOTTRAZIONI
(digits:1=1 digit,2=2 digits,3=3 digits; borrowing: 0b, 1b,2 b; j=jackson test)

Stimoli	Categoria	Risultato	Risposta	RT	Punteggio
13-2	**2-1/0b**	**11**			
15-4	**2-1/0b**	**11**			
57-8	**2-1/1b**	**49**			
73-22	**2-2/0b**	**51**			
97-59	**2-2/1b**	**38**			
7-4	1-1/0b/j	3			
19-7	2-1/0b/j	12			
25-3	2-1/0b	22			
47-7	2-1/0b	40			
96-4	2-1/0b	92			
78-5	2-1/0b	73			
36-8	2-1/1b	28			
87-9	2-1/1b	78			
15-6	2-1/1b/j	9			
43-5	2-1/1b	38			
82-3	2-1/1b	79			
57-21	2-2/0b	36			
83-11	2-2/0b	72			
74-32	2-2/0b	42			
78-46	2-2/0b/j	32			
49-25	2-2/0b/j	24			
27-18	2-2/1b/j	9			
34-15	2-2/1b/j	19			
58-39	2-2/1b/j	19			
33-16	2-2/1b/j	17			
57-18	2-2/1b/j	39			
185-63	3-2/0b	122			
148-32	3-2/0b	116			
247-21	3-2/0b	226			
167-49	3-2/1b/j	118			
119-35	3-2/1b/j	84			
227-56	3-2/1b	171			
176-97	3-2/2b/j	79			
256-67	3-2/2b	189			
242-54	3-2/2b	188			
197-165	3-3/0b	32			
269-187	3-3/1b	82			
346-279	3-3/2b/j	67			
					Totale: /33

TESTING SESSION 2

Jackson and Warrington test (Subtraction):

JACKSON TEST
(Borrowing: 0b, 1b, 2b)

SOTTRAZIONI

Stimoli	**Risultato**	**Categoria**	**Risposta**	**RT**	**Punteggio**
7-4	3	0b			
15-6	9	1b			
19-7	12	0b			
27-18	9	1b			
34-15	19	1b			
49-25	24	0b			
33-16	17	1b			
78-46	32	0b			
58-39	19	1b			
57-18	39	1b			
167-49	118	1b			
176-97	79	2b			
119-35	84	1b			
346-279	67	2b			
					Totale: /14

Arithmetical facts (Multiplication):

FATTI ARITMETICI SEMPLICI
(multiplier: N=bigger,n=smaller; result:M=>10, m=<10; R=rule)

MOLTIPLICAZIONI

Stimoli	**Risultato**	**Tipo**	**Risposta**	**RTs**	**Punteggio**
3x1	**3**	**ES**			
4x3	**12**	**ES**			
7x4	28	N-M			
4x5	20	n-M			
0x8	0	n-m-R			
2x3	6	n-m			
8x7	56	N-M			
1x9	9	n-m			
2x5	10	n-M			
8x5	40	N-M			
6x2	12	N-M			
2x4	8	n-m			
5x1	5	N-m			
3x0	0	N-m-R			
					Totale: /12

Complex mental calculation (Addition):

CALCOLO MENTALE

ADDIZIONI

(digits:1=1 digit,2=2 digits,3=3 digits; carrying: 0c, 1c,2 c;j=jackson test)

Stimoli	Categoria	Risultato	Risposta	RT	Punteggio
14+1	**2+1/0c**	**15**			
15+4	**2+1/0c**	**19**			
56+9	**2+1/1c**	**65**			
32+15	**2+2/0c**	**47**			
47+39	**2+2/1c**	**86**			
9+6	1+1/1c/j	15			
23+2	2+1/0c	25			
35+4	2+1/0c	39			
4+41	1+2/0c	45			
11+8	2+1/0c/j	19			
8+91	1+2/0c	99			
45+7	2+1/1c	52			
38+6	2+1/1c	44			
18+7	2+1/1c/j	25			
5+67	1+2/1c	72			
7+39	1+2/1c	46			
15+13	2+2/0c/j	28			
34+21	2+2/0c	55			
72+17	2+2/0c	89			
24+68	2+2/1c	92			
57+33	2+2/1c	90			
58+15	2+2/1c	73			
43+78	2+2/2c/j	121			
68+34	2+2/2c/j	102			
99+22	2+2/2c/j	121			
68+47	2+2/2c/j	115			
231+65	3+2/0c	296			
147+41	3+2/0c	188			
124+73	3+2/0c	197			
123+29	3+2/1c/j	152			
158+34	3+2/1c	192			
27+191	2+3/1c	218			
89+133	2+3/2c/j	222			
58+147	2+3/2c/j	205			
173+68	3+2/2c/j	241			
236+142	3+3/0c	378			
128+149	3+3/1c/j	277			
244+129	3+3/1c/j	373			
296+174	3+3/2c	470			
				Totale:	**/34**

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